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Editor: G. V. JACKS

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Assistant Editor: DR. D. A. OSMOND

ROTHAMSTED EXPERIMENTAL STATION, HARPENDEN, HERTS.

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AMEN HOUSE, LONDON, E.C.4

THE DISCIPLINE OF SOIL SCIENCE

W. T. H. WILLIAMSON[1]

Is there such a subject as soil science, or is there merely—as one reviewer of a textbook called it as late as 1952—a 'hotch-potch of sciences' applied to the study of soils?

It is strange that the general public does not connect science with such an ordinary, well-known thing as the soil. When one mentions 'soil science', one is met with a quizzical look or a puzzled air and is often asked to spell the first word. One may be known as 'a soil expert', but seldom, if ever, as a 'soil scientist'. You may remember that the doyen of soil science in this college says in his *Mother Earth* that when introduced to people as a soil expert (a title which he himself would never have claimed) either the word 'soil' suggested some ribald joke as to his occupation or else he was asked if he could tell him what was good for the interlocutor's garden. During the war, while in the advisory service, I was attached for a period to one of our larger universities. If ever I entered the staff room, hoping to find relaxation in 'the feast of reason and the flow of soul' for which one looks—and does not always find—in academical circles, almost invariably I was met with some such cry as, 'Oh, here's the man who'll tell me what's wrong with my cabbages.' It was good to know that so many high academicians were allotment-minded and industriously producing extra food for the war-time effort, but somewhat damping to feel one's own status was that of a 'cabbage-doctor'. Can we wonder, when we have been so long tied to agriculture? The Liebig tradition dies hard.

By no means do I wish to underestimate the value of Liebig's work, but it over-emphasized one aspect of the study of soils. It resulted in a one-sided attack on the problem. Chemists analysed samples of soil often with no more effect in elucidating its true nature than the analysis of a haggis would have in explaining the behaviour of a sheep, even though, I would have you know, a haggis contains most of the vital organs of that animal. Once more I do and indeed must, as a quondam chemist myself, recognize the value of a knowledge of chemistry in connexion with the study of soils. I need hardly tell this audience that even our empirical methods of soil analysis—especially during the last war—prevented hundreds of crop failures and resulted in greatly increased yields in other cases. On a higher plane than that of practical applications it is impossible to study soils without the use of the techniques of chemistry. That, however, is not the whole story and I have come to deplore the title of 'agricultural chemistry' in connexion with the study of soils. Think what the position of chemistry itself would have been today if it had remained tied to medicine—as it was in some places—or that of geology if tied to mining and quarrying.

[1] Presidential Address delivered in the University College of North Wales, Bangor, 7 Sept. 1958.

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Not only the chemists, but also the physicists, the bacteriologists, the geologists, and others have often approached the study of the soil merely as an application of their own science to a particular case. Too often investigations have been divorced from the soil as it is in nature. We all know instances where a mechanical analysis, while useful in giving the distribution of the ultimate particles, will not indicate the behaviour of the soil in the field. The production of so many triangular diagrams is merely a reflection of this fact. Many of us prefer the finger test for specifying the field behaviour and E. W. Russell, on page 76 of *Soil Conditions and Plant Growth*, boldly proclaims its superiority. Mechanical analysis does not take account of the differences in the properties of the particles, particularly those of the clay minerals. We have in the north of Scotland a particular soil which is most intractable in the field and yet by the old method of mechanical analysis it had only 9 per cent. clay. Even by the modern method it has only a little over 20 per cent. clay and about the same amount of silt. Then there are cases where bacteriologists may isolate organisms from a soil and find that in pure culture they produce this or that substance. Does it necessarily follow that the same reaction will take place when the medium is the soil itself and there are possibilities of interactions with other organisms? Again much of our attention has been absorbed in attempting to solve *ad hoc* problems. As G. V. Jacks says in his book *Soil*, we have been so busy attempting to solve such problems that we have not had time to formulate general principles. Vast quantities of information have been amassed, but from it all have we got an organized body of knowledge that can be called a single science or do we lay ourselves open to the accusation of 'fragmentation' so often brought against us by those belonging to what some are pleased to call 'the muck and mystery school'?

Is it not strange that, while for long we have had in botany a science of the plant, some are still arguing whether we have a science of the medium in which plants live? Recent advances in botany, it is true, have come about through the application of the fundamental sciences of mathematics, physics, and chemistry, but an organized body of knowledge was long and well established before these times. In the study of soils, we seem—in this country at any rate—to have started the other way round. Eighty years ago in Russia Dokuchaev was teaching that 'the soil was very much like a living thing, born of parent rock and slowly developing under the influence of other factors'. A soil as a sort of biological entity? Whether we agree entirely with this or not, it seems essential that a soil should be studied in relation to its origin and environment, just as a plant would be. Something in the way of a biological outlook is necessary and that, for those of us who come from the physical sciences, is not so easily acquired. The investigator must know what he is dealing with in all its aspects. He must clearly distinguish between 'soil' and 'a soil'. He must recognize the individuality of soils. That is no new thing. Virgil in the *Georgics* says, 'Nunc locus arvorum ingeniis; quae robora cuique quis color'. (Now is the time to describe the innate natures of soils; what vigour and force and what colour to *each* belong.)

To return to my original question—have we still two schools of

thought? *A* science or a hotch-potch of sciences? N. H. Taylor, in his excellent first presidential address to the New Zealand Society of Soil Science, made these remarks: 'Unfortunately, neither the body of knowledge nor the attitudes of mind of the specialists engaged in soil work are so fully unified as we could desire. The integration of the two schools of thought has been a slow process and even in New Zealand today evidences of the cleavage persist.' We might add that this applies equally in our own case.

I am well aware that much is done in the way of the co-ordination of investigations. We have the excellent efforts in this way of the Agricultural Research Council and its various committees; we have the work of the directors of the research institutes and there are many other instances of like endeavours that could be cited. But do we do enough ourselves to know what the other fellow is talking about? Is the training of our workers all that could be desired? Too often the young graduate in one or other of the so-called pure sciences is pitch-forked into soil work in a research institute, the advisory service, the soil survey or such-like without any previous training in the approach to the study of soils and it may take him some time to find his feet. Some of us have experienced the young chemist to whom the soil is simply another substance for chemical treatment. He may isolate an organic compound from it, but he is far more interested in this and its constitution than in its mode of origin in the soil and its function therein. Then there is the new recruit from geology, who is absorbed with the rock material in the bottom of a cutting, while the old hands, from whom he might learn something, are studying the soil face. Very essential it is, too, to know the parent material, but, again, that is not all the story. Many of these young men and women turn out excellent workers with a wide appreciation of soils in all their relationships, but their path is often a rocky one and there are some who never seem to get their feet on the ground. Would not their path be smoothed and their usefulness enhanced by some previous training? It should not be necessary for the research station, the soil survey or other similar organizations to undertake preliminary training in the study of soils.

I asked a few minutes ago whether we do enough to know what the other fellow is talking about. Do the chemists or the physicists always know what the pedologist is talking about or vice versa? Do the pedologists always understand one another? I mentioned the old hands at the soil face and we all know what I call 'the argument at the face'. There will always and indeed must always be differences of opinion, but are we agreed on essential points? How many, for instance, would agree on what is a 'podzol'? I have found wide interpretations of that one term. There are other terms which have strayed far from their original meaning. I might cite the case of 'catena', which now seems to be used in some very different senses from that of Milne's original concept. From the teaching point of view, in particular, it would be useful to have at least some degree of uniformity or some semblance of co-ordination. Discussions in some of the journals in recent years indicate the reality of the want of this. Some have even gone as far as to doubt the

usefulness of pedology. But can we do so? Certainly not as one aspect of the study of soils. But I think that we have too many theories and even speculations without sufficient basis in facts. Much more investigation on a quantitative basis is required—such as more chemical and other interpretations of morphological characteristics. It is good to know of some interesting and encouraging efforts in this co-operative direction, but there is still need for the pedologist to explain his problems to the chemist and the other specialists and to prove that here there are subjects for investigation worthy of the highest skill—and for the others to listen to him. These others should remember, however, that the pedologist is observing the soil in its natural state and that such observations can be just as scientific as the reading of a dial in the laboratory. In one of his papers L. G. Romell refers to 'a curious modern tendency to regard everything recorded by apparatus in the laboratory as being more scientific than visual observations in nature'.[1] Accurate recording of morphological features is often an essential prerequisite to investigations involving the so-called exact sciences. Attention paid to it would make these investigations more real and more intimately related to the living body of the soil.

For the most part we have come to the study of soils trained in different disciplines and I hold that this study has a discipline of its own. Many of us have discovered its discipline, or, at least, humbly think we have. The more we can integrate and co-ordinate our knowledge by intercommunication the sooner we can establish that organized body of knowledge with agreed principles and unified discipline that can be called a science. Then and then only will there be no argument as to whether or not there is such a subject as soil science.

(*Received* 28 *October* 1958)

[1] Cornell University Agric. Exp. Stat. Memoir 170 (1935).

GENERAL CONSIDERATIONS ON THE PROBLEM OF SOIL CLASSIFICATION

G. MANIL

(*Laboratoire de Pédologie, Gembloux, Belgium*)

I. *Introduction*

AT the 6th International Congress of Soil Science, held in Paris in 1956, I submitted a synthesis of the general problem of soil classification. Taking that report as a starting-point I now wish to submit for discussion some general considerations suggested by various classification schemes presented at or before the Congress. It seems worth while trying to elucidate a few definite issues, while excluding, if possible once for all, several false or insoluble problems which sometimes still result from lack of mutual understanding. Experience has indeed shown that specialists are often very near agreement when they have succeeded in restricting the discussion to a limited number of issues. It seems no mere wishful thinking to say that even now international agreement is quite possible on the fundamental aspects of the problem of soil classification.

II. *The Problem of General Classification*

A. *Preliminaries*

(*a*) Definition of the subject. As Stewart (1954) and Stephens (1954) have pointed out, there are three groups of problems to be solved, (i) definition, (ii) nomenclature, (iii) classification. But before attempting an examination of specific issues of definition, it is necessary in my opinion to reach agreement on a number of general principles of classification itself so as to put an end to the confusion and misunderstanding that sometimes still prevail among pedologists.

(*b*) Definition of the term 'classification'. As is usually understood, a *classification* constitutes a co-ordinated, synthetic and, if possible, natural system of grouping different objects which are generally classed at several levels of generalization. As a matter of fact, confusion still exists, especially in oral discussion, between *method of classification* and *methods of classing*. Classing is accidental and corresponds in principle to a well-defined practical purpose. It may be merely geographical, as in the case of *association*, in the commonly accepted meaning of the word. For practical reasons of land use or soil conservation, soils which are adjacent to one another in a geographical unit must sometimes be grouped together technically, although they may be placed far apart in a proper classification. The best-known association, the *catena*, corresponds to topographic juxtaposition. The necessity for such a method of grouping also appears when printing a pedological map, even on a large scale. It is not generally possible to reproduce in all particulars all the soil formations actually identified in the field.

Another method of classing that is often used for utilitarian and specific purposes is the division into *phases*. Phases are used in large-scale mapping, when it is worth while giving prominence to some well-defined ecological or technological factors which can often be expressed by 'single values' such as useful depth of soil, content of nutrient elements, pH, humus content, slope, &c. The phases may correspond to natural division into types, series, or other units of classification; but they may also be spread over several such units.

In spite of the necessity to make use of such phases for some practical purpose, it is not possible to include all imaginable phases in a complete system of classification. If this conclusion is accepted, a frequent cause of argument and misunderstanding will have been ruled out. In other words, it must be acknowledged that the best system of classification will never be able to give all the information necessary for all practical purposes. In addition to a general system of classification, with all its usefulness, it is necessary to allow in some cases for another method of classing soils. In botany, for instance, it is not possible to include in one and the same systematization the classification by anatomical and physiological characteristics and the utilitarian properties of plants.

B. *General notes on the problem of soil classification*

(*a*) To begin with, why do several kinds of soil classification exist, whereas there is, in general, international agreement on botanical, zoological, mineralogical, &c., classifications?

This side of the problem has already been the object of numerous comments which amount to saying that *soil is a multi-dimensional system in space and time*; as Bergson would have said, the actual description of a given soil appears to us with all the static quality of a picture of a moving object. Accordingly, soil cannot be defined with absolute rigour. At any level of generalization whatever, a definition of it is always partly imperfect and arbitrary, like the definition of all complex things, such as works of art. Moreover, the terms that we use to describe a specific pedological formation can never be identified with pure ideas, with abstractions. It must be admitted as a matter of fact that lecture-room discussions slip all too easily into abstractions instead of dealing with actual soils.

In practice, however, the pedologist still often comes up against the following difficulties:

1. The technical (often merely financial) impossibility of determining all the important properties of known soils with adequate accuracy. It is enough only to mention the hydrological properties of soils.
2. The scale and purpose of the work, about which more will be said later.
3. The difference of method and accuracy in the description of various characteristics of soil. Even if accurate means of determining definite properties of soil are used, it is none the less true that different authors are apt to be at variance in setting limits between two closely related soils. Such discordance is likely to be still more marked if the descriptions are purely qualitative.

4. Differences in frame of mind according to race and form of civilization. Some types of culture favour reasoning from ideas to facts, others from facts to ideas. It should not be overlooked, as Leeper (1956) points out, that it is sometimes possible to detect behind arguments issues of national, political, or racial prestige.

(*b*) *'Natural' or 'universal' classifications.* When discussions are held there appears to be a misunderstanding which it is desirable to clear up. Care must be taken to distinguish between *natural classifications* and classifications founded on natural characteristics, often immediately perceptible. As several colleagues have pointed out, the former should command 'natural', unquestionable recognition by the very nature of the things it aims at classifying. Most workers are convinced that such a system is not even conceivable, and would set more realistic bounds to their ambitions, hoping, however, that in the not too distant future pedologists would agree on a *universal classification*, i.e. universally accepted after discussion and mutual concessions. It might simply be a system universally accepted as a system of reference without necessarily being universally applied.

(*c*) *Complete or incomplete classifications.* A classification is *complete* when it includes all categories, from the most general to the most detailed category which makes large-scale mapping possible. A classification is *incomplete* when the highest or the lowest categories are missing. For example, it is incomplete at the bottom when it deals only with the higher categories, in which case its chief interest lies in the scientific side, though it could be used for the schematic description of vast areas as natural regions. A classification is incomplete at the top when the pedologist turns his attention exclusively to those lower categories which are essential for more immediate practical purposes, as is often the case in soil surveying.

Most of us would grant that it is possible for one specialist to construct a complete classification. It should be noted, however, that in the setting up of higher or lower categories different considerations and a different frame of mind are at work and these cannot always be reconciled in actual fact. To make this point clear, it is enough to point to the frequent arguments between two groups of pedologists. Those on the practical side tend to regard classifications that are incomplete at the bottom as a product of purely academic labour, eminently respectable perhaps, but without practical meaning. On the other hand, those concerned only with the higher terms are sometimes tempted to look down on practical classifications, incomplete at the top, as a more or less incoherent juxtaposition of facts which it would be difficult to integrate into a co-ordinated system. It is a manifestation of the ever-recurring controversy between the theoretically and practically minded people.

I propose to limit the discussion to the various types of complete classifications.

(*d*) (i) *General characteristics of various types of proposed complete classifications.* A classification can be represented as a more or less truncated pyramid. The top corresponds to the number of highest categories in the classification, e.g. 10 for that used in France and 12 for

that used in Russia. The base may be very wide, depending on the number of lower categories—usually very large. Whatever the method of classification, it may be asked whether there do not exist levels of categories more or less common to all proposed systems, and, of course, there are.

Descending the scale of categories, there is towards the base a level at which one finds definite categories, more or less comparable with botanical or zoological species. At this level, for instance, a given soil may be described as 'le sol brun lessivé sur loess'.

In several classifications, specific terms are found down to a level which, to use a commonly accepted word, we shall call 'series'. In polytype series or complex series it is necessary to go down to types or subtypes, i.e. to terms suitable for practical large-scale cartography. Just below the top of our truncated pyramid there is a level at which the characteristics are specific enough to make a representation of the soil possible as, for instance, in a sketch. Such a sketch could be used to represent an iron podzol in general, but it obviously cannot be used to convey such qualities as zonality in a soil.

The following table is a tentative linking of the reference levels of several types of classification. We have included in it the German classification of Mückenhausen (1954), those of Avery (1956) for Britain and Stephens (1954) for Australia, and also that of Kubiëna (1953), although they apply only to limited areas. Their chief interest lies in the tendencies. Since this is not meant to be a complete synthesis it was not thought necessary to mention all classifications that have ever been proposed.

Types of classification	*Higher level*	*Lower level*
I. Australian. Stephens (1954)	Great soil groups	From the series or down, types and phases
II. Kubiëna (1953)	Types	Lokalformen
III. U.S.S.R. Ivanova (1956)	Types	Species and varieties
IV. French. Aubert and Duchaufour (1956)	Sub-groups, sometimes groups	From the series or down
V. German. Mückenhausen (tentative scheme, 1954)*	Types	Facies
VI. British. Avery (1956)	Sub-groups	Series and sub-series
VII. U.S.A. (tentative scheme, 1956)†	Upper categories VI and V	Series or types

* Quoted by kind permission of Prof. Dr. E. Mückenhausen.
† Quoted by kind permission of Dr. C. E. Kellogg and Dr. G. D. Smith.

It should not be very difficult for the authors of these various schemes to agree on the definition or on the naming of the reference levels. This would be a decisive step towards the elaboration of a universal system of reference.

(ii) *The method of elaboration.* There are two main methods of working. The first is analytic and descending: it starts from general facts and principles and goes down to more and more detailed categories as observation proceeds. The second method is synthetic or ascending: a

great many data are first gathered and then classed into more and more general categories.

In the analytic method, which is usually genetic, there are again several ways of working according as one relies directly on some pedogenetic factors, pedogenetic processes, or properties that reflect genetic characteristics. The synthetic method may rely on morphological characteristics chosen with or without pedogenetic considerations or various chemical, physical, &c., characteristics chosen objectively because of their practical importance, but without genetic considerations.

It is appreciated that it is not possible to define the various types of classification rigorously in a single phrase, but it does not seem absurd to describe some of the tendencies of the proposed systems in the following terms:

1. Descending classification based on the genetic factors: U.S.S.R. system proposed by Ivanova (1956).
2. Descending classifications based on pedogenetic processes: French system (Aubert and Duchaufour, 1956), Kubiëna's system (1953), German system (Mückenhausen, tentative scheme, 1954).
3. Descending classifications based on properties that reflect pedogenetic factors or processes: British system (Avery, 1956), Australian system (Stephens, 1954).
4. Ascending classification based chiefly on morphology, with pedogenetic considerations: U.S. system (tentative scheme, 1956).
5. Ascending classification based on various characteristics objectively chosen for their practical value without pedogenetic consideration: Leeper's scheme (1954).

Broadly speaking, it can be said that a descending system is the only possible one when no large amounts of accurate data are available, as in the form of small-scale soil maps. The classification may then be of the *a priori* type, in which case it must be improved as new findings are made. Descending systems are of necessity essentially genetic, since only the previous knowledge of the genetic factors or processes makes deductive reasoning possible. For instance, it may be assumed *a priori* that, in an area whose climate and geological structure are known, the soils will come under one of the great soil groups such as 'Sols bruns' or 'Chernozem'.

An advantage of the ascending type of classification is that it is founded on a large amount of detailed data resulting chiefly from soil surveying. It is accordingly rather of an *a posteriori* type. Serious difficulties may, however, be occasioned when it comes to elaborating higher categories from a large number of data spread over a lower level.

(iii) *Types of construction.* Another characteristic which could possibly be used to distinguish between types of classification is the *type of construction*. Ideally, the best solution would be a *simple construction*, characterized by more and more detailed subdivision of a single factor, according to a single phylum—*simple classification*, but owing to the complexity in the origin of soils and the number of characteristics necessary for their description, this method is purely theoretical and unsuitable in pedology. *Mixed classification* is already more complex. It assumes a different but single factor at each level of categorization.

Empirical classification is founded on several factors at one and the same level of categorization, in order to take into account the full complexity of soils. The various systems mentioned above fit, on the whole, with this type of construction, which, logically, is the least perfect, but, practically, the most used by soil specialists.

C. *Attempting to simplify the issue*

In discussions on soil classifications the various issues are easily multiplied as experience often shows. The main thing is to determine those which are really worth considering, to limit their number and discuss them in turn. It is generally acknowledged that agreement has been reached on the following points:

(i) It is necessary to make a clear distinction between questions of definition, nomenclature, and classification.

(ii) The adoption of an international system of taxonomy is not yet possible. It is necessary first of all to reach agreement on numerous problems of definition and nomenclature.

(iii) It is already possible to exclude a number of issues with which the discussions often become involved to no avail. This could be achieved (*a*) by not confusing problems of *soil classification* or *taxonomy* and problems of soil *classing*, and (*b*) by limiting discussion to types of *complete classification* or, at least, to systems that have reached the same degree of elaboration, in order to avoid the misunderstanding that often arises between theorists proposing classifications incomplete in the lower parts and practical workers offering systems incomplete in the higher parts.

(iv) The first main theme for discussion could be a comparison of the advantages and disadvantages of the methods of elaboration in systems of classification, both of ascending and descending methods. However, it appears that in our present state of knowledge both methods are necessary for mutual control.

(v) A study of the *descending* methods leads, as we have shown, to a first rough division into three groups, which could probably readily be reduced to one system. It would be easiest, as a first step, to determine the similarities between the units included at the *higher level* that can be represented by sketching a profile, as has been mentioned above.

(vi) However, as it is certainly premature to try to elaborate a single system at present, it is more convenient to propose a *common system of reference*, for which we would suggest the French system of Aubert and Duchaufour. This has the advantage of being, at one and the same time, both complete and general, and standing between two extremes. Indeed a pedogenetic process stands between the pedogenetic factors and the properties brought about by pedogenesis. If it be done in a constructive spirit it would be worth while attempting to find links with the provisional reference system which would doubtless lead to the elaboration of an *international reference system of soil classification*. The idea of such a system would appear, for the present at least, less Utopian and of more practical interest than a *universal system* that would stand little chance of being used by everybody.

D. *Notes on some problems of immediate interest*

Recent pedological literature and reports by participants in the discussion during the Paris Congress raise a number of issues of immediate importance in soil classification. It is satisfactory to note that the opinions expressed were in general identical. We shall consider three issues which, if discussed, might lead quickly to complete agreement.

(*a*) *The utilitarian trend in soil classification.* As we have already shown, an unquestionably 'natural' classification is hardly conceivable. It is not even possible to find single terms to express all the complexity of any object whatever at any level of generalization. A system of taxonomy is necessarily a compromise between purely scientific and speculative logic and some practical necessities. Economic and social needs which are now arising all over the world demand that pedological problems, often of a purely cartographical nature, should be solved. This makes it a duty to direct the work of soil classification and mapping towards utilitarian aims, as far as is compatible with serious scientific work. In order to be utilitarian, classification must, at least in the lower categories, provide surveyors in charge of pedological map-making with the simplest criteria possible. Preference must be given to morphological characteristics, on condition that these have a real agronomical meaning, i.e. that they correspond to factors of unquestionable importance for the growth of plants and the technology of soils.

(*b*) *The trend towards 'actual' description of soils.* As our knowledge increases, chiefly as a result of cartographic studies, it is ever more clearly noticeable that the characteristics used to define a pedological unit at any level of generalization have no clear-cut limits, either in time or in space. There is a 'law of continuity in time' and a 'law of continuity in space', as Duchaufour pointed out.

The first of these two laws is expressed by the fact that we notice more and more frequently the presence of paleopedological characteristics, especially in those parts of the world that have remained free from the recent alterations of the Quaternary ice ages. The most logical and convenient way of handling this time factor is to include those characteristics in the lower categories, for instance, at the level where variations of parent material appear.

Let us take the case of soils of recent, almost present-day, genesis like those of temperate zones, which were covered with forest after the latest glaciations. Alterations of this vegetable cover brought about by the latest post-glacial climatic fluctuations and the influence of man caused certain pedological properties, which are still generally considered as being actual, to become fossil. There are, for instance, typical *grey-brown podzolic soils* or *sols bruns lessivés* or *Parabraunerde* which have in fact become *sols bruns acides* of the A/C type. We also know *podzols* of typical morphology that, to judge by the type of humification and the nature of vegetation (*chènaie à charme*), now function like *sols bruns*.

It is for this reason that we are often compelled, for practical and ecological reasons, to introduce two different concepts in the interpretation

of profiles (Manil, 1956): (1) the pedological profile, and (2) the edaphic profile. A *pedological profile* is defined by its general morphological genetic characteristics to the exclusion of clearly paleopedological features.

An *edaphic profile* is defined by its biological tendencies and more particularly by its type of humification.

(*c*) *The trend towards giving the human factor all its actual importance.* It becomes more and more evident that man has played an essential part in the genesis of the present properties of our soils by modifying the vegetal cover; by being the indirect cause of numerous forms of alteration by erosion, or inversely, by accumulation of particles brought by wind, running water, or gravity; by modifying in one way or another the quantity of water percolating through the profile, or by modifying the position of the underground water table; and by adding organic or mineral amendments and fertilizers to the soil, and so on. Among pedological formations which have reached some degree of development there are seldom any to be found which can be regarded as being 'virgin' or 'natural'.

There is a real difficulty in choosing the level of categorization at which the human factor is to be introduced. Agreement is far from being general on this point. The problem becomes somewhat simpler when soil is studied with its actual particularities. It would become still simpler, however, if provision were made in the classification for pedogenetic processes which would specially take human influence, direct or indirect, into account. This question alone would deserve a full report which would certainly not fail to make further discussions more profitable and less academic.

One process which is typically of human origin could be recognized at once, and it might be termed *catenization*. Over an area whose soils are assumed to be homogeneous at the outset, clearing and especially deforestation lead to erosion which brings about the succession in space of more or less eroded profiles, and more or less colluvial or alluvial profiles following one another in 'catena' form according to Milne's conception of the word.

III. *General Conclusions and Proposals*

A. The systematic examination of the various types of proposed classifications shows clearly that there is no fundamental opposition between the workers on the problem. Moreover, agreement is getting more and more general on the three trends specially mentioned above, namely, the utilitarian trend, the priority of actual characteristics, the importance of the human factor.

B. Co-ordination of endeavours at the international level could easily be achieved in two stages:

(*a*) preliminary choice of one system as a provisional *frame of reference*, for which the French classification seems to be the most suitable;

(*b*) starting from this, one could elaborate an *international system* which should be checked by comparison with both the descending and the ascending systems of classification.

Acknowledgements

It is my duty to recall here the part taken by prominent scientists in the general discussion, opened on the occasion of the last Congress in Paris, on the general problem of classification of soils, and more especially by Messrs. Aubert, Avery, Duchaufour, Edelman, Ehrart, Ivanova, Glangeaud, Kellogg, Kovda, Kubiëna, Mückenhausen, Muir, Smith, Stremme, von Kries, Yerokhina, Zavalashin, and others. I have much pleasure in expressing my deepest thanks to Dr. Muir, past Chairman of the 5th Commission of the Congress, 1956, for his kind assistance in reading over the manuscript of this paper.

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THE RUSSIAN APPROACH TO SOIL CLASSIFICATION AND ITS RECENT DEVELOPMENT

J. J. BASINSKI[1]

Summary

Due largely to the conditions in which they were working, Russian pedologists were the first to establish pedology as an independent science. From the beginning they regarded soil as an independent body with a definite morphological organization, expressed mainly in the structure of the profile, and resulting from pedogenetic processes determined and directed by environmental factors. This concept of soil led them to adopt a genetic approach to problems of soil classification. Russian soil classifications differed according to the basis accepted, whether bioclimatic, geographical conditions, factors of pedogenesis, pedogenetic processes, or soil evolutionary history. In recent years attempts have been made to construct classification systems based on all these aspects of pedogenesis. The current Soviet trends in soil taxonomy must be regarded mainly as a further development of the traditional approach. Measures are taken to standardize soil nomenclature and improve methods of recognizing (diagnosing) and describing soil types, which are regarded as basic taxonomic units. The evolutionary-genetic approach is considered the only proper approach to soil-classification problems. The importance of organic aspects of soil evolution and formation processes is emphasized. More attention is given to the genetic subdivision of soil types into smaller and better defined soil groups. Interest in the systematics of cultivated soils is also growing.

I. *Introduction*

Ever since Dokuchaev (1879) published his first classification of the soils of Nizhnyi Novgorod Province in 1879, the minds of Russian pedologists have been exercised by the problems of soil taxonomy, probably far more than those of their Western counterparts. Russian literature on this subject is so voluminous that to summarize it for the English reader would involve prolonged and intensive study but for a number of excellent reviews published recently, mainly in one of the journals of the Soviet Academy of Sciences, *Pochvovedenie* (*Pedology*).

The number and extent of quotations from early works found in contemporary Soviet literature on soil taxonomy and used in support of current arguments are striking to the Western reader. It is, however, the best evidence of the evolutionary rather than revolutionary development of Russian thought on the subject. All recent developments are so closely linked with past achievements that it is impossible to consider them apart from the traditional Russian school of pedology and the conditions under which it developed.

II. *Traditional Russian Approach to Soil Science as a Whole*

Russian pedologists have been fortunate in the geographical position of their country—in the middle of the Eurasian continent—and its vast extent. They have been able to study a wide variety of environments and vegetation types as well as soils, and to make extensive comparisons. This has also undoubtedly led to the broad outlook which has persisted

[1] Division of Land Research and Regional Survey, C.S.I.R.O., Canberra, A.C.T.

in their thinking. In addition, the presence of soil undisturbed by man in a wide range of environmental conditions makes it possible for them to be studied in their natural state and form.

The Russian school of pedology in general and soil classification in particular must also have been influenced appreciably by the fact that it developed under the stimulus of the necessity of classifying and mapping land for utilization purposes often without the opportunity of studying it intensively.

The mental climate of Russia in the late nineteenth and early twentieth centuries must also be taken into account. It was the time when modern scientific thinking, seeking not only to establish and record the facts and laws of nature, but also to explain them, received its main impetus. The teaching of Darwin and his disciples often provided the basis of explanation, and hence the evolutionary approach was fashionable.

While western European and American scientists were still considering soil as a geological material (Hilgard) or a complicated mixture of chemical compounds (Liebig), the early Russian pedologists were the first to regard soils as an independent body with a definite morphological organization reflected in the profile. They were the first to show the broad but definite inter-relationship between environment, soils, and vegetation, and the first to recognize soil as the product of a process governed by environmental factors rather than by soil parent material. This led to recognition of the fact that soil is a dynamic and not a static body, a living organism allied in the plane of development to biological bodies.

This Russian concept of soil and its place in nature has, in the words of Marbut (1936), 'established [the study of soils] firmly as an independent science with criteria, point of view, method of approach, process of development applicable to soil alone and inapplicable to any other series of natural bodies'. It also had a predominant influence on the development of Russian taxonomy.

III. *Traditional Russian Approach to Soil Classification*

One of the primary aims of soil-classification systems as proposed or employed by Russian pedologists since the time of Dokuchaev's first soil classification is to group the soils according to their productivity and utilization problems, and to determine, compare, and explain their fertility differences. Dokuchaev (1893), writing of his first classification, stressed 'the close connexion existing between soil types on the one hand and yields, kind of crops and husbandry methods on the other'. In many recent papers on the subject, Russian pedologists continue to stress the importance of soil productivity in taxonomic work. For example, Ivanova (1956) states, 'fertility is an essential property of the soil and consequently soil classification must reflect this property'. She writes further, 'soil world groups, constituted on the basis of radiation energy, define the main ways of utilizing natural resources in national economy. Classes and subclasses define the type of husbandry. Soil types, regional groups, families, subtypes and forms permit more concrete zoning of types of agriculture and husbandry systems, give indispensable ameliora-

tion measures, define the order of soil suitability for cultivation, use in agriculture etc.' This stress on utilization aspects in the Russian approach to soil taxonomic work is often forgotten by those outside observers who lose themselves in the theoretical and philosophical arguments of Russian pedologists.

The Russians have always recognized the 'genetic soil type' as the fundamental unit. Their classification schemes are essentially a series of attempts to link soil types into progressively larger groups and to subdivide them into progressively more defined variants. The definition of soil type is usually based on three criteria first established by Sibirtsev towards the end of the last century, namely:

1. Sameness of genetic properties of the soil.
2. Sameness of the pedogenetic processes determining these properties.
3. Sameness of pedogenetic factors defining and directing the pedogenetic processes.

The choice and extent of the 'genetic soil properties' taken into account when defining 'soil types' have differed from time to time, although the morphological structure of the profile has always been of primary importance. Moreover, since the days of Sibirtsev, Russian pedologists have considered that only the combination of the attributive and genetic approach can lead to an identification of soil types and their classification which will permit the proper appraisal of soil fertility. This point of view is still generally accepted amongst them (Rozov, 1957).

Because one of the fundamental concepts of pedology as developed mainly in Russia is that soil is a product of geographical environment which determines the process of its formation and which is in itself a resultant of separate environmental factors, the attention of Russian soil classifiers has, since early days, focused on environment, environmental factors, and pedogenetic processes rather than on the soil itself.

It is true that the father of Russian soil taxonomy, Dokuchaev, stressed in connexion with his first classification that 'grouping of the soils should always be based on the sum of existing characters of a given body' (its profile, clay content, chemical characteristics, &c.). As pointed out recently by Rode (1957), however, 'many of Dokuchaev's followers, amongst whom were some eminent scientists, did not always adhere to this principle, and developed their own classification schemes, basing them mainly on conditions of pedogenesis'. Even when the properties of the soils themselves provided the basis of a classification system, the classifications as such were based on genesis rather than on soil attributes, on the assumption that all soil-material characteristics are merely the reflexion of their development processes as directed by environment.

Also, because soils and their pedogenesis are regarded as a single system, it is often very difficult for outside students of Russian pedology to distinguish whether the reference or argument concerns soil as such or the process of its formation, which to a Russian are one and the same thing. This is well illustrated by a recent review of soil-classification systems by Gerasimov (1954) who, dealing for example with Kossovitch, Tumin, Glinka, Gedroitz, Neustruev, and Prasolov's systems, describes

them as 'based on intrinsic properties of the soil', while in fact they are based on intrinsic soil-forming processes.

The existence of a definite relationship between geographical environment, soil, and its vegetative cover on which Russian classifications are based, justifies also the inclusion of environmental (geographical) and ecological terms in the classification systems.

The evolutionary character of soil formation makes it possible to explain soil differences as expressions of different stages of their evolution as well as expressions of different conditions governing evolutionary processes. This concept of soil as a product of evolution has played an increasingly important part in the thought of Russian pedologists and in their approach to soil classification.

The experimentation in soil genesis and evolution has not yet been developed as a well-established method of attack on the problems involved. Consequently, reasons for the soil differences found in the field or laboratory must be reached by interpretation of correlations between soil types and factors influencing its development. In this deductive approach to soil taxonomy, Soviet scientists are prepared to go much farther than Western pedologists.

IV. *Differences in the Russian Approach to Soil Classification*

All Russian soil classifications are based on a genetic approach. However, within this general approach five different categories of classification systems may be recognized, according to whether the systems are based on conditions of pedogenesis, the factors governing pedogenesis, the character of pedogenetic processes or evolutionary stages in these processes, or a single process. This grouping of then existing classification systems has been adopted by Gerasimov (1954) in his recent review. His terminology, however, when translated is apt to confuse the Western reader, and has not been adopted here in its entirety.

(*a*) *Geographic-environmental classifications*

In these classification systems the soil types clearly related to bioclimatic conditions of regions where they are found are classed as 'normal' or 'zonal'. Those not so related are classed as 'transitional' and 'abnormal' or 'intrazonal' and 'azonal'.

Thus, Dokuchaev (1896) in his final classification grouped glacial, light grey podzolic, brown forest, chernozemic, dark chestnut, light greyish brown, red, dark brown swampy and whitish secondary solonetz soil types into the class of 'normal' or 'zonal' soils. He also recognized a class of 'transitional' or 'intrazonal' soils, and a class of 'abnormal' or 'cosmopolitan' soils, including aeolian, alluvial, and swampy soil types.

Sibirtsev (1895, 1898, 1900) classified soils into classes and types. The class of 'zonal' soils included the following types: lateritic, aeolian loess, desert-steppe soils, chernozemic, grey forest, grassland, podzolic, and tundra soils. The 'intrazonal' class included solonetzic, swamp, and humic-carbonate soil types. The class of 'azonal' soils included skeletal, coarse, and riverain types.

In the classification proposed by Afanasev (1922, 1927) who in the

1920's developed further the ideas of Dokuchaev and Sibirtsev, each of five climatic belts (cold, cool, temperate, subtropical warm, and tropical hot) is divided into two complexes, maritime and continental. Each soil type has an equivalent in the corresponding complex. Further subdivision is based on soil changes as influenced by the type of vegetation (forest, grassland-forest, and grassland). Finally, differences due to different phases of evolution influenced by degradation and salinization processes are also considered.

In constructing classification systems in this category, the authors—as stated by Sibirtsev (1895)—attempted 'to explain the soil cover of the earth's surface in its genetic entity and geographical variability'.

(*b*) *Factorial classifications*

These classifications are based on separate factors of pedogenesis or their combinations. Glinka (1902, 1915), who was the first to adopt this approach, divided soils into two main groups, 'ectodynamomorphic' and 'endodynamorphic'. The former is the result of external (mainly climatic) factors, while the character of the latter is determined by the parent material. Further classification is based on the moisture régime.

Vilenskii's (1925) classification is typical of this category although, like Dokuchaev, he divides soils into 'zonal' and 'intrazonal'. Zonal soils in his system are divided horizontally into five belts, based on Köppen's temperature zones (polar, cold, temperate, subtropic, and tropic) and five corresponding soil divisions (hydrogenic, phytohydrogenic, phytogenic, thermophytogenic, and thermogenic). Each of these belts is subdivided vertically into columns according to Weigner's humidity regions (arid, semi-arid, weakly arid, semi-humid, and humid). Intrazonal soils are divided horizontally into five divisions (halogenic, phytohalogenic, hydrohalogenic, thermohalogenic, and thermohydrogenic). The first two divisions correspond to the temperate zone and the last two to the subtropical and tropical zones. The first two are also divided vertically according to humidity regions. In addition, the soils of the mountain region are grouped in the orogenic division.

Zakharov's (1927) system is essentially similar, zonal soil complexes being divided into climatogenic, orogenic, hydrohalogenic, fluviogenic, and lithogenic divisions, and classified further according to climatic and ecological conditions.

Vysotskii (1906) also divides soils into zonal, intrazonal, and undeveloped, subdividing them further according to climate and parent material.

The most recent factorial classification is that of Volobuev (1955) who groups the soils into climatic communities, subdividing each community into two orders: automorphic and hydromorphic. Swamp soils and solonchaks are regarded as intrazonal soil types. Further classification is based according to vegetation communities associated with the soils.

(*c*) *Process classifications*

These classification systems are based on differences and similarities

in the process of soil formation. As has already been pointed out, owing to the lack of distinction between the processes and their result, some of the Russian soil taxonomists who adopted this approach claimed that their classifications were based on intrinsic soil properties, although in fact they were based on the pedogenetic processes.

Kossovitch (1910), for example, wrote, 'genetic soil classification should be based on intrinsic properties and characteristics of the soils themselves'. In his classification, however, he divided soils according to types of pedogenesis. In the group of 'genetically independent' (eluvial) soils he recognized the following types of pedogenesis related to bioclimatic conditions: desert type, semi-desert (solonetzic) type, steppe (chernozemic) type, humid-cool (podzolic) type, humid-hot (lateritic) type, and polar (tundra) type. The class of genetically dependent (illuvial) soils embraced the corresponding types of pedogenesis as affected by impeded drainage. In the case of each type of pedogenesis, transformation and translocation of mineral and organic substances were considered, special attention being given to changes in organic matter.

Tumin's (1907) classification is basically the same. His classes were divided into families according to quantitative expression of the pedogenetic process (degree of development), and some families were subdivided into forms, e.g. podzols were divided into podzols proper, podzolic and weakly podzolic, while chernozems were divided into chernozems proper and southern chernozems. There was also division into groups according to parent material.

Glinka (1922, 1924), in his later work, recognized five basic types of pedogenesis (lateritic, podzolic, chernozemic, solonetzic, and swampy) and stressed that since pedogenetic processes lead to transformation of organic matter and decomposition of mineral matter and translocation of the products of these two processes, the soil properties are born in pedogenesis itself.

In Neustruev's (1926) classification there are two broad divisions of soil-forming processes, 'automorphic' active under normal moisture conditions, and 'hydromorphic' active under conditions of excessive moisture. The processes are further subdivided according to their effect on the state of decomposition of the mineral constituents, transformation of organic matter, and translocation of the products of pedogenesis.

Prasolov (1934) classifies the processes into eluvial, salinizing, and desalinizing, and hydromorphic. According to his system, eluviation results in three principal soil groups: soils of the humid regions, soils of the semi-humid and semi-arid regions, and soils of the arid regions. These groups are further divided into genetic soil types defined on the basis of interrelation between biological elements (mainly vegetation) and parent material on the one hand and pedogenetic processes on the other.

(*d*) *Evolutionary classification*

Although his classification in its final form was based on types of pedogenesis Kossovitch (1906), in his earlier work, regarded soils as phases in evolutionary development governed by two processes based on

acid and alkaline weathering. His ideas undoubtedly influenced other Russian soil taxonomists.

In Polynov's uncompleted classification, the influence of Kossovitch's concept can easily be recognized. Polynov (1933) considered that soil evolution proceeds along two lines, one governed by eluviation and one by salinization or desalinization. In the eluvial evolution, Polynov recognized two basic processes, acid and alkaline weathering, and considered that soil types merely reflect evolution's many stages due to progressive de-alkalinization. Thus alkaline weathering produces alkaline, pre-chernozemic, and chernozemic phases, while acid weathering results in prepodzolic, podzolic, and swampy phases. With increased humidity, alkaline weathering may give place to acid weathering and thus the two series may be regarded as continuous. Halogenic evolution consists of phases corresponding to transition from the solonchak group through the carbonic group to the swamp group.

Until recently, Viliams's (1939) concept of a single pedogenetic process—a part of his much wider theory of environment and life evolution—completely dominated Soviet pedology. This, according to Rozov (1957), is at least partly responsible for 'many unclear and undecided theoretical problems in [contemporary Soviet soil] science'. The wide concept of Viliams undoubtedly stimulated thought, but, being advanced dogmatically, it was also placing thought in 'chains'.

Viliams regarded soil evolution as a phenomenon connected with geological history of life on earth, as a part of a single process of life development. Since living organisms affect soil development directly and indirectly through their effect on environment and pedogenetic processes, life was also considered as the main moving force in pedogenesis. Consequently, the processes of synthesis and decomposition of organic matter are regarded as particularly important in soil formation.

In addition, Viliams's theory postulates that soil evolution proceeds along a single path determined by the development of relief and shifts of climatic conditions and vegetation zones. For example, he thought that 'all the great territory in the U.S.S.R. in turn passed through all the phases of pedogenetic evolution, beginning with tundra'. Thus, according to his theory, all existing soils represent merely different phases in a single evolutionary development, being simply a function of time.

Recently this approach has been strongly criticized by Soviet pedologists. However, during the time when Viliams's views reigned supreme, a number of attempts were made to classify soils entirely in accordance with his principles. Tsyganov's (1955) classification may serve as an example. It is based on a single process of evolution connected with the geological growth and drying out of continents. The swampy, podzolic, grassland steppe and desert soils are regarded as evolutionary zonal phases with intrazonal phases based on the development of relief.

V. *Recent Development in the Russian Approach*

Recent trends in Russian pedology in general and soil taxonomy in particular cannot be described as revolutionary. They constitute merely a further development of the traditional school of thought of Dokuchaev

and his early successors, and of Viliams and his followers. The genetic-evolutionary approach still universally accepted is, however, based on a much firmer foundation, made possible by the ever-increasing volume of pedological material. Especially since the 1939–45 war, Soviet soil-survey and mapping activities have been considerably increased, to embrace the lesser known polar and tropical regions of the Soviet Union. Close co-operation with eastern European and Chinese scientists has extended the zone of activities of Soviet pedologists even further and has brought new, often valuable minds to the Russian school of pedology. Material for soil inventories has been greatly extended and, since the war, the compilation of such inventories has taken a place of great importance in Russian work. Field and laboratory studies of different soil types also have been intensified and made more detailed.

(*a*) *Standardizing nomenclature and methods of diagnosis of soil taxonomic units*

As may easily be understood from the preceding sections, which describe the development of Russian pedology and soil taxonomy, soil nomenclature and methods of recognizing and defining taxonomic units were, until comparatively recently, allowed to develop without any check or co-ordination. This inevitably led to a great profusion of ill-defined technical terms and diagnostic methods, resulting in constant misunderstandings and general confusion. Since the war, work has begun, mainly in the Soil Institute of the Academy of Sciences of the U.S.S.R., to bring order to this chaos in nomenclature and methodology. This culminated in the appointment by the Academy of Sciences in 1956 of a special permanent commission including forty leading Soviet pedologists. Opening the first session of the Commission in February 1957, the Chairman, Academician Tyurin, stated that 'the main task of the Commission appears to be unification of soil nomenclature, systematics and methods of diagnosis. These topics cannot, however, be discussed apart from classification problems. The Commission, although it is unable to undertake the task of developing classification schemes, which is beyond its powers, can nevertheless direct this work by considering them and making the necessary recommendations.'

The minutes of this first meeting (Rozov *et al.*, 1957) stress the considerable discrepancy in the meanings of many pedological terms in the minds of different workers. The Commission began its work by defining soil types and subordinate units:

Type

Major soil group, developing in a single type of bioclimatic and hydrological conditions, characterized by a clear manifestation of the basic processes of soil formation, possibly in combination with other pedogenetic processes. Characteristic points of soil type are defined by:

(1) same type of accumulation of organic matter, its rate and character of distribution;

(2) same type of processes in decomposition of mineral substances and synthesis of new mineral and organic-mineral products;

(3) same type of translocation of soil materials;

(4) same type of structure of soil profile;
(5) same direction of measures for increasing and maintaining soil productivity.

Sub-type

Groups of soils within the range of soil type differing qualitatively in the manifestation of one of the superimposed soil-forming processes and in the intensity with which they reflect the main pedogenetic process. Measures for increasing and maintaining soil fertility are more alike for a sub-type than for a type.

In differentiating a sub-type, the subzonal as well as regional change in environmental conditions is taken into account. (Zonal conditions in the Russian approach are those determined by latitude or altitude—i.e. mainly temperature; regional conditions are determined by the type of climate, continental or maritime.)

Family (*Rod*)

Group of soils within a sub-type, with qualitative peculiarities dependent on local conditions, for example parent material (including chemistry of ground water), past history of soil development (relics of previous stages), &c.

Form (*Vid*)

Soils within family divisions differing in the degree of development of pedogenetic process (degree of podzolization, quantity of humus and strength of humic horizon, degree of salinization, &c.).

The Commission also recommended further study and discussion of methods of recognition of soil types and their description as the basis of future standardization. Since its first meeting Rode (1957) has published a very interesting paper on this subject in which he stresses the necessity of basing genetic soil classification on a proper recognition ('diagnosis') of different soil types. This diagnosis, he advocates, should be based on a wide use of the methods of chemical and physical analysis, as well as on field observations. He also recommends, as far as possible, a quantitative approach to the definition of soil taxonomic units. According to him, these units should be based on similarity of a wide variety of soil attributes. These should be presented in the form of curves illustrating changes in different properties within the soil profile.

He considers that each soil type or lower taxonomic unit should have its own 'passport', a document containing the following parts:

1. Morphological column illustrating schematically the morphological structure of the soil profile by the use of agreed symbols.
2. A very short morphological description of separate horizons corresponding to their illustrations in the morphological column.
3. Graphs illustrating distribution in the profile of various soil characteristics, e.g. clay fraction, humus, carbonates, total salts, exchangeable bases, pH, &c.
4. Graph of mechanical composition.
5. Graph of moisture and other physical properties.
6. Graph showing root distribution.
7. Graph showing distribution of main groups of organic matter.
8. Graphs showing schematically the characteristic points of water and heat régime, &c.

Rode considers that these soil 'passports' should play a most important

part in the preparation of soil-classification systems. Finally, he advocates the establishment of soil collections which should have a similar function to that of herbaria in plant taxonomy.

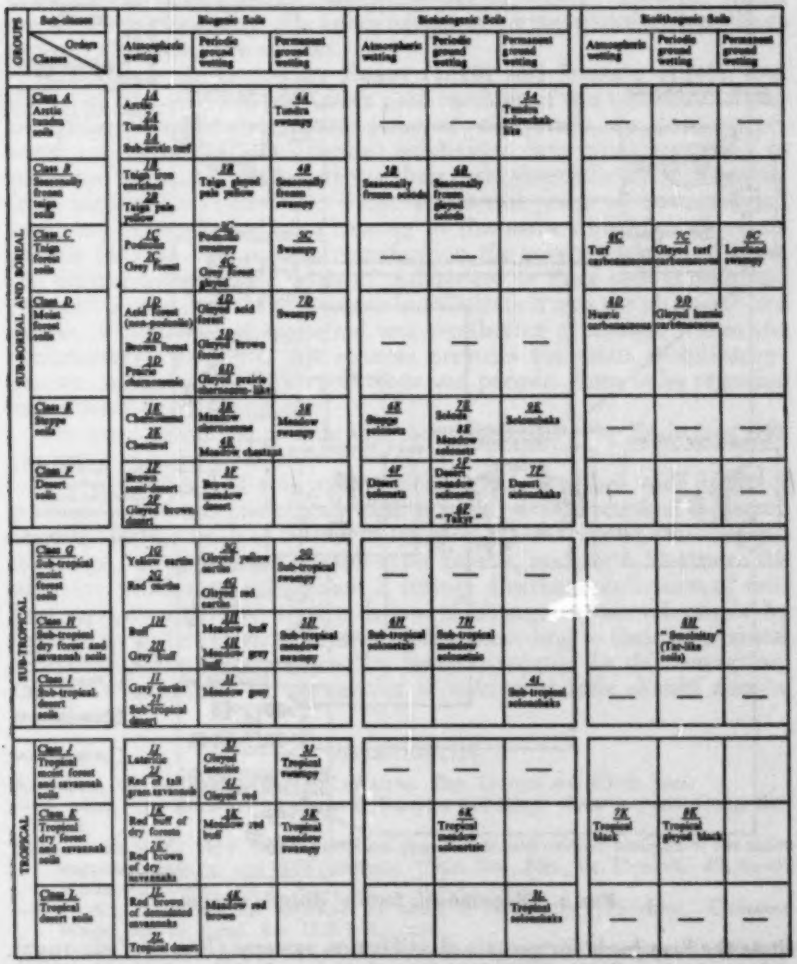

FIG. 1. Tabular representation of Rozov's (1956) scheme for the genetic grouping of soil types showing their evolutionary-genetic relationships.

(*b*) *Approach to classification*

The genetic approach is still accepted by Soviet pedologists as the only right approach to soil classification. As we have already seen, Viliams's theory of a single pedogenetic process has lately been subjected to considerable criticism. However, many Soviet pedologists still regard

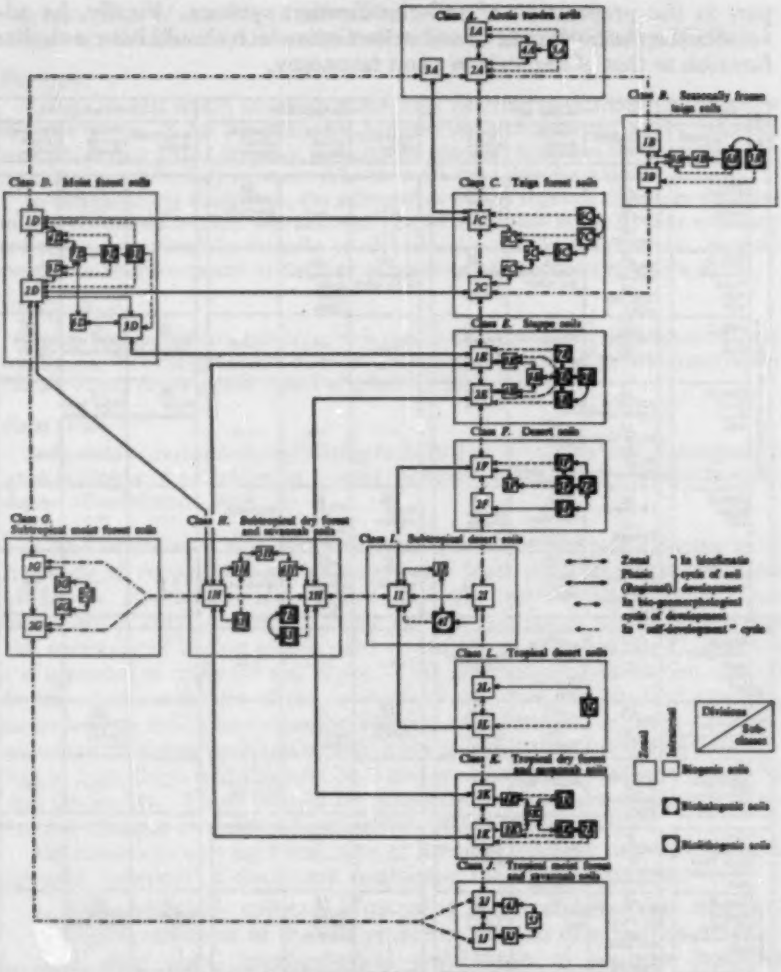

FIG. 2. Diagrammatic form of Rozov's scheme.

it as the best basis for genetic classification systems (Rozov *et al.*, 1957). Moreover, in all current attempts to devise such systems, the evolution concept plays a very important part.

The predominant significance of biological and biochemical processes in soil formation is also universally accepted, though weathering of minerals and translocation of mineral compounds currently receives more attention than in the years when Viliams dominated Russian pedology. At the same time the importance of the direct influence of vegetation on pedogenesis is unquestioned.

Within the framework of the genetic evolutionary approach, the question of whether genetic soil properties and processes or conditions of pedogenesis and pedogenetic factors should be taken as the basis of classification is still alive. New ideas are emerging, however, which envisage the possibility of a combination of all the traditional methods to form a classification system.

The system developed by Rozov (1956) and Ivanova (1956), and shown in Figs. 1 and 2, provides a good example of this tendency. From the geographical-environmental point of view, soils are divided into zonal and intrazonal, and further subdivided into types according to zonal and regional characteristics of their pedogenesis resulting primarily from bioclimatic conditions. From a factorial point of view, the soil types are vertically linked according to the main complexes of pedogenetic factors. For process classification the seventy-seven soil types are differentiated on the basis of differences in their pedogenesis and grouped on the basis of differences in salinization and the character and degree of influence of biological and weathering processes. From the evolutionary viewpoint, this scheme presents the main evolutionary-genetic connexions between soil types and permits them to be regarded as historical-genetic phases.

The same combined genetic approach is advocated by Rode (1957) in the paper mentioned above.

The subdivision of soil types which include a rather wide range of genetically and morphologically similar soils has also received increased attention in the work of Soviet pedologists. The recently standardized definition, quoted above, of sub-type, family, and form illustrates the direction which type subdivision is taking. Further subdivision of soils into variants according to the degree of change of natural profile by cultivation and erosion, and into varieties according to their mechanical composition has been proposed by Ivanova (1956). In this connexion, the growing interest in systematics of cultivated soils should also be mentioned.

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THE CLASSIFICATION OF GILGAIED SOILS: SOME EVIDENCE FROM NORTHERN IRAQ

S. A. HARRIS

(*Land Use Division, Hunting Technical Services Ltd.*)

Summary

The discrepancies between the classifications of McGarity and Hallsworth *et al.* are summarized and confirmed with later descriptions by other writers.

Further evidence from Northern Iraq shows that gilgai occurs which forms a transition from normal to 'tank' form in several topographic types. A further form of depression gilgai is described completing the four possible combinations of the lattice-A, wavy, and normal gilgai of Hallsworth *et al.* Depression forms from the limit of the area in which gilgai occurs are described.

A new classification into gilgai types (based on topography and dominance of shelf and puff) and varieties (based on the nature of the puff and the size of puffs and channels) is suggested.

Introduction

PRESCOTT (1931) introduced the aboriginal word 'gilgai' into Australian literature for certain regular forms of microrelief induced by alternate seasons of wetting and drying of clay soils. Although many other names have been used locally in Australia, this term has now come into use in many other countries. The exact equivalence of examples in different areas remains uncertain. Assuming that the Australian, African, and Iraqi gilgais have a common cause, it is the purpose of this paper to discuss the existing classification of these peculiar soils in the light of further evidence from northern Iraq.

Past Work

Prescott did not subdivide gilgais. In subsequent years a considerable amount of scattered morphological information was published in the C.S.I.R.O. bulletins. The Australian gilgais were subdivided into the upstanding part (the puff), the sloping part (the shelf), and the actual depression (the channel).

The first comprehensive classification system appears to be that of McGarity (1953). Using the term 'melonhole', he recognized three main topographic types depending on the slope of the land on which they were formed, viz. wavy (steepest slopes), network, and normal melonholes. The network group was further subdivided into a type A where the puffs were dominant, and a type B where the shelves and channels were dominant. In his normal melonhole, the puff and shelf were of equal development.

All the gilgais considered by McGarity had a hard surface to both puff and shelf. However, he mentioned another type in which a soft puff occurred. In his types with a hard puff, no evidence of upward movement and mixing of material in the puff could be found even though

carbonate concretions were present in the profile. Unfortunately his paper merely summarized his views and no detailed evidence has been seen by the present writer.

Two years later, Hallsworth, Robertson, and Gibbons (1955) published detailed evidence regarding the variety with the soft puff, and produced a more complex classification, using the now widely accepted term gilgai. The topographic classification of McGarity was used apparently without knowledge of his earlier paper. The normal or round puff was upstanding (the mushroom gilgai) and a type with sink holes, the topographic form corresponding to the 'network melonhole' of McGarity, was called 'lattice gilgai'. These were subdivided into lattice A (shelf dominant) and lattice B (puff dominant)—the reverse of the name classification of McGarity. The gilgais with the hard surface to the puff were included as 'melonhole gilgai' without any subdivision according to topography. The difference between puff and shelf was ill-defined in these soils. In contrast to McGarity's melonholes, the gilgais with soft puffs showed evidence of movement around puff margins as well as shear planes in the profile. A new group, the 'tank gilgai', was introduced for cases where the puffs and shelves were of exceptional size. Typical examples had puffs 10 m. wide and shelves 20 m. by 10 m. in area. A further group, the 'stony gilgai', was used to describe areas where stones, brought up from below, occurred on the soft puff surface. These occurred in all the major topographic forms.

Stephen *et al.* (1956) have recognized what they called 'normal gilgai' on the Athi Plains in Kenya. The puffs were described as 'very slightly raised' and were 20–50 m. in diameter, i.e. the proportions found in the tank gilgai. From the description given, the puff soils appear to be friable while the shelf soils are hard, i.e. they are not of melonhole type. No channels were described, so that they were probably of the mushroom group of Hallsworth *et al.*

In the same paper, further examples from Nyasaland and Tanganyika are mentioned. They seem rather like the mushroom gilgai of Hallsworth. This form has also been described to the writer as occurring on the 'dhambo' soils around the Elephant Marsh in the Shire Valley, Nyasaland (personal communication by Mr. V. C. Robertson and Dr. R. Smith).

Two new complex forms associated with depressions have since been described from central Iraq (Harris, 1958). Type-A depression gilgai consisted of a complex of wavy and normal gilgais. Other permutations are clearly possible; type B with lattice-A gilgai separating the normal and wavy phases was also noted. In addition, both lattice type-A and round gilgai were found on their own in different parts of the area. All these were of the melonhole type, and seemed to have the same relationship to topography as the type with the soft puff described by Hallsworth. This evidence vindicated, once again, the topographic classification, but it was suggested that both the melonhole and stony gilgai should be regarded as variations.

Clearly, the subdivision of gilgai has become inadequate and it is time to attempt a new classification.

Evidence from Northern Iraq

Recently, the author took part in a reconnaissance soil survey of 2,500 sq. km. of land west and south of Kirkuk, northern Iraq. Numerous gilgais occurred within the area and included further undescribed varieties.

The gilgai types found in the Kirkuk area were: (1) depression gilgai, (2) tank gilgai, (3) round gilgai—the commonest form.

Depression-A gilgai occurs locally in the irrigated areas in slight depressions. Farther west, near low hills of gypseous material and in gullied areas, compound forms consisting of complexes of round and lattice-A gilgai occur (Pl. I). These may be called depression-C gilgai and indicate shallow, almost imperceptible relief. They appear to be another example showing up the degradation of relief after the cessation of irrigation (Harris, 1958) since the western half of the area has been irrigated in the past. A form, depression D, containing all three basic types is also formed (Harris, 1958, Pl. III).

Tank gilgais are present in the south-western part of the area. They mainly occur in the form of round gilgai and show up very well on aerial photographs taken after rains (Pl. II). However, caution is required since excessive rain will flood scattered normal gilgais to such an extent that they simulate tank gilgais. Types intermediate between the normal sized and tank forms may be found in all the three topographic forms of gilgai. This variability in wavelength was also noted by Hallsworth *et al.* (1955, p. 13) and experience in northern and central Iraq seems to indicate that there is a complete transition from normal to tank form. Why this occurs has not yet been investigated.

In the same area occurs a peculiar pattern on the air photographs that closely resembles tank gilgai (Pl. III). This turned out to consist of man-made pits up to 25 m. by 60 m. long and often laid out in a pattern resembling lattice-B gilgai. The spoil was piled around the hollows which were dug by the people who dwelt in the towns and settlements whose remains now stand on the nearby gypsum hills. The present-day inhabitants of the area use them for watering sheep and providing summer grazing for their flocks. Some may also be used for rice cultivation. On drying out they are found to be occupied by small depression gilgai, the type depending on the contours of the floor.

The north-eastern limit of gilgai in Iraq is also found in the Kirkuk area, although gilgai also continue in the extreme south of the area on the other side of the Lesser Zab (Binnie *et al.*, 1956, vol. 3). In their marginal form, depression-A and normal gilgais show up weakly on the air photographs (Pl. IV), but are almost indistinguishable on the ground, since they have an amplitude (i.e. difference in height between crest and gully) of about an inch. Careful examination from the top of a landrover shows that the wavelength remains the same; the amplitude is the only thing that changes. Recent measurements of the field permeability in the moist state show that the same relationship occurs in these marginal forms as in full-scale Iraqi gilgai, i.e. moisture penetration is greatest in the shelf and least in the margins. This is the same as was found in the

Deniliquin Irrigation District of Australia by Williams (1953). At Kirkuk, the abundant shallow gypsum horizons act rather in the same way as a coarse textured horizon. Even the hardest and most dense gypseous horizon collapses on wetting.

Thus the forms found in northern Iraq show similar characteristics to those described from central Iraq and Australia. As before, no evidence for separation of the upstanding part into puff and shelf has been found. It has therefore been decided in future to assume that the puff element is absent in Iraq soils, until evidence is found to the contrary.

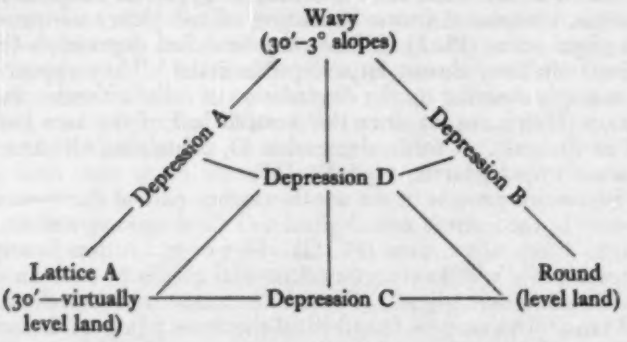


FIG. 1. Relationship between wavy, round, and lattice-A gilgai types, and the associated complex forms in Iraq.

Suggested Classification

A satisfactory classification system of a particular group of soils must be based on the most important common characteristics and variations present in the group. The choice of the system necessarily depends on the state of knowledge at the time it is produced and on the personal opinions of the author. In view of the considerable increase in information now available on gilgai the time seems right for a reappraisal of their classification.

The only common factor throughout all these studies is the dependence of gilgai type on the topography. This is particularly well shown by the occurrence of complex forms.

Fig. 1 shows the relationship between wavy, round and lattice-A gilgai types and the depression gilgai in Iraq. The type of depression gilgai found is an excellent indicator of the nature of the slopes in any depression in which they occur.

So far the reason for the dominance of either puff or shelf in lattice or normal gilgai has not been determined. In the case of the gilgai with a soft puff, the puff consists of subsoil material with mixing taking place at the junction between puff and shelf (personal communication from Prof. Hallsworth). In the melonhole gilgai of Iraq there is negligible differentiation into puff and shelf but 'cauldron faulting' on a minor scale occurs in the depression, permitting the central block to drop down

TABLE 1. *Evidence for Varieties of Gilgai Described by Various Authors*

Gilgai Type		*Characteristics*		*Puff absent*		*Soft Puff*			*Melonhole*
Major	*Minor*	*Slope*	*Puff-shelf*	*Holotype*	*Tank holotype*	*Holotype*	*Tank holotype*	*Stony holotype*	*Holotype*
	Wavy	3°–30′	All cases			Hallsworth *et al.*, 1955		Hallsworth *et al.*, 1955	McGarity, 1953
Lattice	Lattice A	30′–Virtually level	Shelf dominant	Harris, 1958		Hallsworth *et al.*, 1955		Hallsworth *et al.*, 1955	McGarity, 1953
	Lattice B		Puff dominant			Hallsworth *et al.*, 1955	Hallsworth *et al.*, 1955	Hallsworth *et al.*, 1955	McGarity, 1953
Normal	Round	Virtually level	Shelf dominant	Harris, 1958	†	Hallsworth *et al.*, 1955		Hallsworth *et al.*, 1955	Hallsworth *et al.*, 1955; McGarity, 1953
	Mushroom		Puff dominant			Hallsworth *et al.*, 1955	Stephen *et al.*, 1956*	Hallsworth *et al.*, 1955	Muir in Stephen *et al.*, 1956; Robertson and Smith †
Depression	Depression A	Complete depression forms	Shelf dominant	Harris, 1958	†				
	Depression B			Harris, 1958					
	Depression C			†	†				
	Depression D			†After Harris, 1958					

* See text p. 28. † Described in this paper.

nearly 30 cm. This difference may well be connected with some factor such as the ability of a given soil type to transmit pressures. No intermediate forms have been described. The forms of gilgai in Iraq include only the shelf-dominant types; presumably at least four further groups of complex forms are possible corresponding to the puff-dominant combinations with wavy gilgai. The likelihood of a shelf-dominant form producing a complex with a puff-dominant form is uncertain, but if so, further complex types may be found.

From the point of view of classification, the major gilgai types are best regarded as being the key topographic forms, the term 'normal gilgai' being used to include both mushroom and round gilgai. Minor gilgai types may be used to denote the several forms of the depression, while the dominance of shelf and puff can also be used in the cases of lattice and normal gilgai.

From a study of the likely overall cause of gilgai, Harris (1958, p. 182) suggested that the gilgais with a soft puff were due to more extreme gilgai-forming conditions than the melonhole gilgai. For this reason, these may be taken as the major varietal factors. The Iraq forms without a puff are also provisionally separated. In two of these cases there seems to be an enlarged form possible which has been described from certain areas, while stony gilgais occur in the basic topographic groups of the soft puff variety. From the evidence from Iraq, a transition in wavelength from holotype to tank form seems to occur.

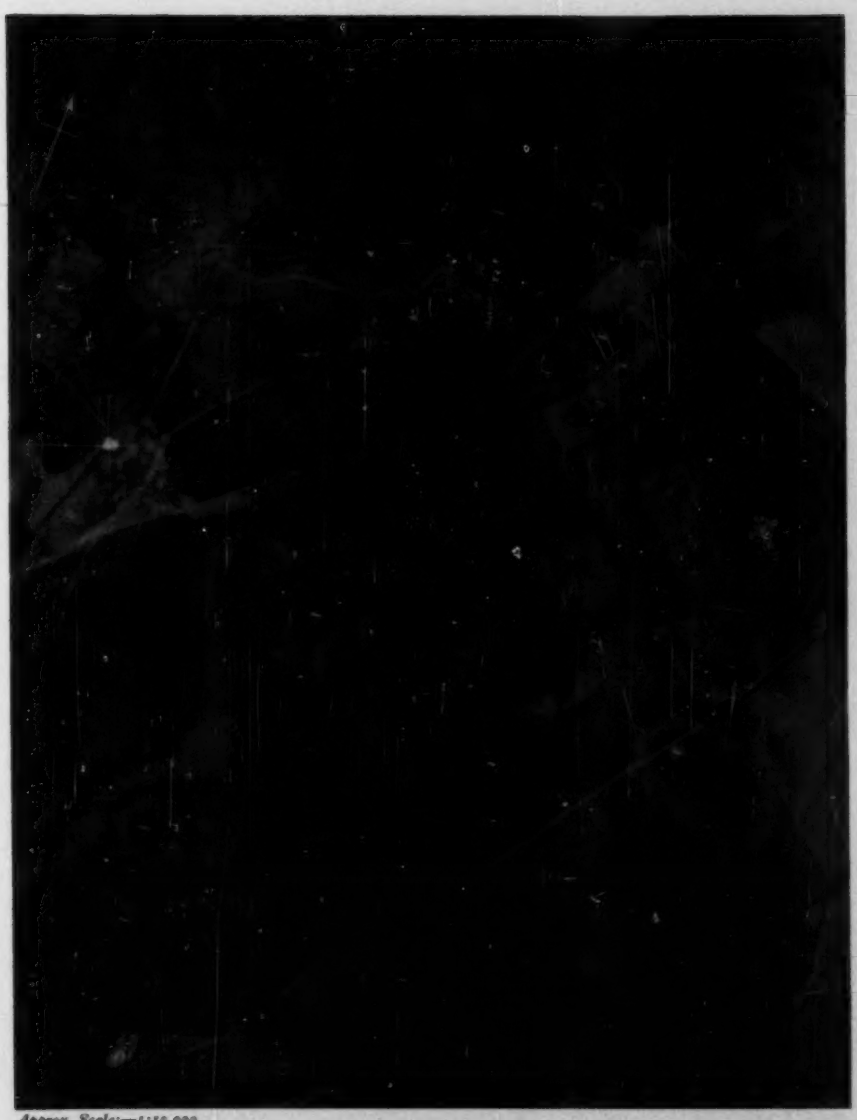
Table 1 summarizes the evidence for this classification. The reference to each gilgai variety so far recognized is also included. Basically, it differs from the classifications of both Hallsworth *et al.* (1955) and McGarity (1953) by accepting both the soft puff and melonhole gilgai as being of equal status, while differentiating more clearly between the importance of the various factors, e.g. topography and the appearance of stony and tank gilgais. Further evidence from northern Iraq gives more information regarding both tank and depression gilgais of the melonhole variety.

Conclusions

An attempt is made to reclassify the numerous gilgai types described to date. The division into major gilgai types is made on the basis of topography. Where necessary, subdivisions into minor types are made on the basis of dominance of puff or shelf and on minor topographic differences in the complex depression forms.

Three chief varieties are recognized, viz. the gilgai with a soft puff, gilgai without puffs, and the melonhole gilgai with hard puff. Further subdivisions into varieties is based on the presence of unusually large puffs and channels (the tank gilgai) and on the appearance of stones and concretions on the surface of the puff in stony gilgai.

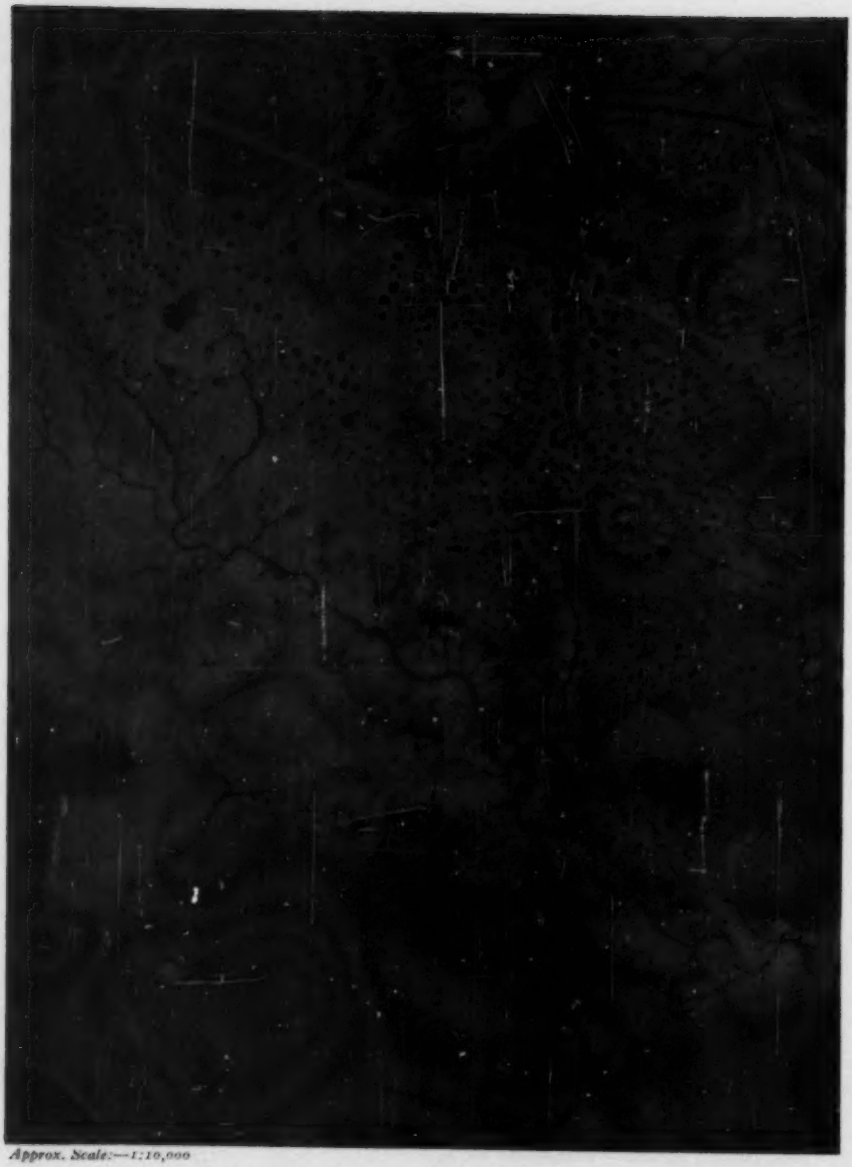
If a simplification is required, then the subdivision of varieties into tank and stony gilgai would seem of the least value. Until more is known about the cause of the relative dominance of puff and shelf, these would seem best retained unless a really drastic simplification be required.



Approx. Scale:—1:10,000

Depression-C gilgai, 10 miles SSE. of Hawiji, North Iraq

S. A. HARRIS—PLATE I



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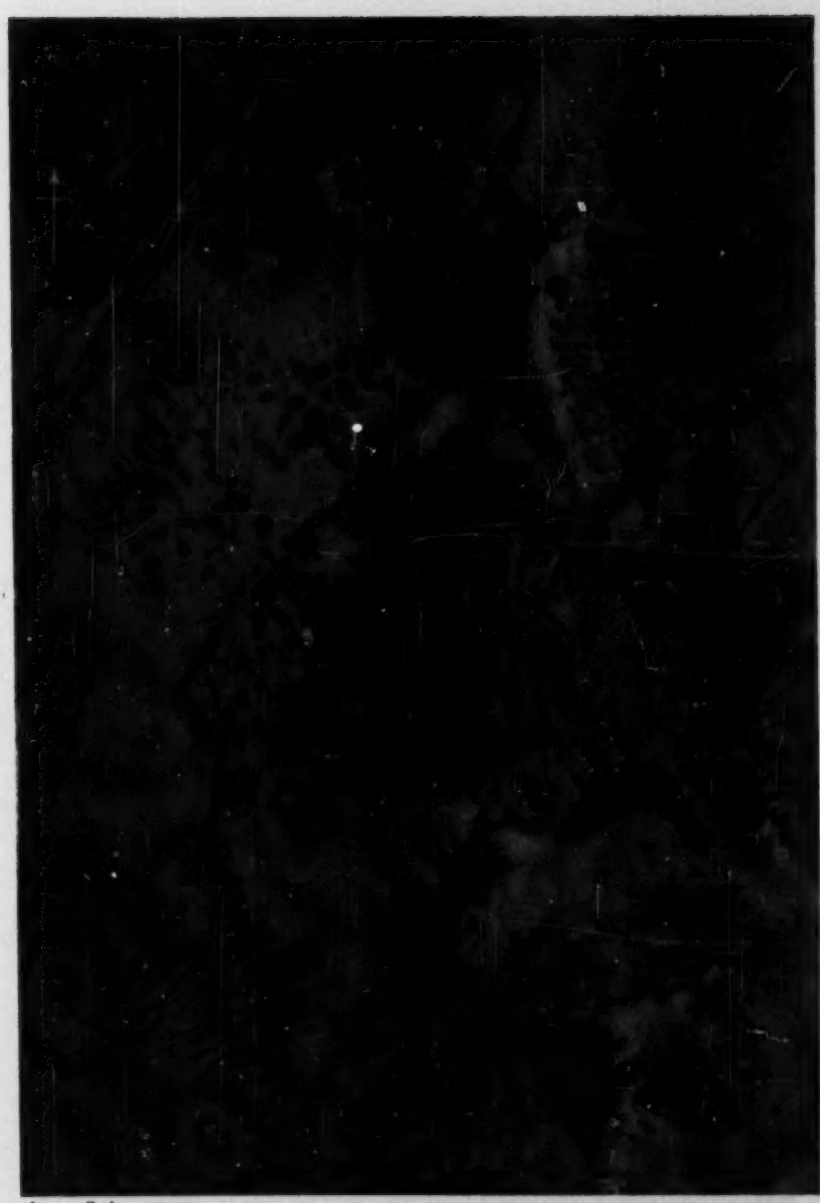
Tank and normal sized round gilgai near Zighatun Chai, N. Iraq

S. A. HARRIS—PLATE II



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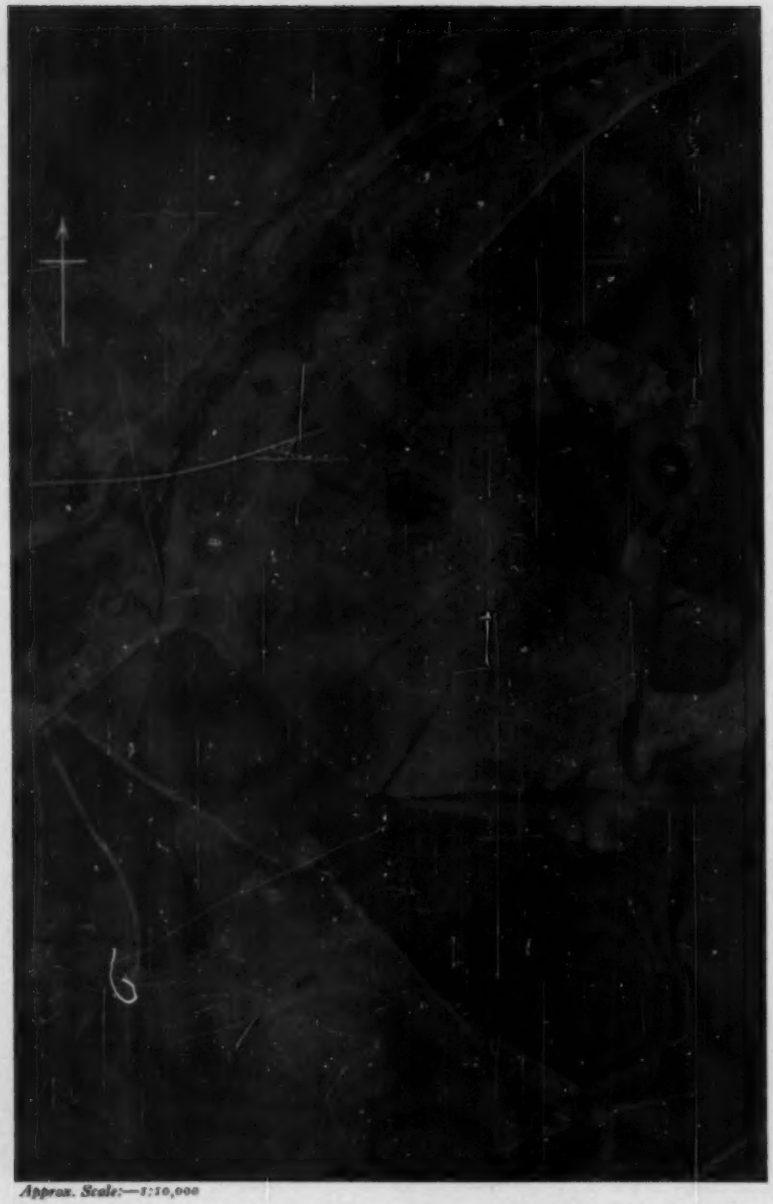
Man-made pits resembling tank gilgai from the area near the junction of the Zighatun and Tauq Chais. Gypsum hills, old canals, Depression-C and normal type gilgai complete the pattern. The land is rather saline. Note the old settlement

S. A. HARRIS—PLATE III



Approx. Scale:—1:10,000

Gilgais at the extreme limit of their occurrence. These gilgais are almost indistinguishable on the ground owing to their extremely low amplitude

S. A. HARRIS—PLATE IV

Acknowledgements

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THE BUTANA GRASS PATTERNS

G. A. WORRALL

(*Faculty of Agriculture, University of Khartoum, Sudan*)

Summary

A study has been made of the features associated with repeating bands of vegetation in the Butana region of the Sudan. Aerial observations show that they have similar features to those described by MacFadyen in British Somaliland except that the curved bands lie on the interfluves and are convex downslope.

The patterns consist entirely of grasses and herbs, and lie on very gentle slopes of about 1 in 200; there is no measurable difference in elevation between the grasses and bare areas. Slopes of less than 1 in 500 have no patterns. The width of the bands is variable, but commonly between 8 and 12 m., and the bare ground about twice the width of the grass.

The profile consists of a grey-brown clay loam, with an A horizon slightly lighter in colour and texture. No difference in profile, composition, or properties between the soil under grass and under bare ground has been detected, except in pH, nitrate, and moisture. There are differences in soil surface, the bare areas being smooth and the grassed areas broken by cracks and potholes which form at the beginning of the rains and concentrate just upslope of the previous season's grass. Experiments to simulate on the bare ground the moisture and growth conditions obtaining under the grass bands were partially successful.

The current season's grass concentrates at, and in advance of, the previous season's front, and there is an annual migration of the grass bands upslope.

The vegetation consists dominantly of the grasses *Aristida* spp., *Schoenfeldtia gracilis*, *Cymbopogon nervatus*, and *Sehima ischaemoides*. Species of grass may have a restricted position in the grass band, the most striking being *Schoenfeldtia*. Herbs are more ephemeral, but are prominent during the rains in the old grass areas.

The origin of the patterns appears to be related to water supply, topography, and soil, but not to wind. Comparison with gilgai is made, but reasons are given for considering that the patterns have a different mode of origin, and an initiation due to a type of soil slip or to a rhythmic deposition of vegetation is considered possible.

THE occurrence of vegetation in the form of repeating bands was first recorded by MacFadyen (1950*a*) in British Somaliland and later described in detail by him (1950*b*). Similar patterns have been observed in other parts of semi-arid Africa on both sides of the Equator, including the Sudan where they have been studied by the present writer for the past two years. Two distinct types have been distinguished, one consisting entirely of grasses and herbs and occurring on clay land known as the Butana, east of Khartoum, and the other in which trees are prominent, occurring on red sands known as *goz* in the west of the Sudan particularly between El Obeid and Fasher, and just north of Malakal in the southern Sudan. The latter type has been observed from the air, but as yet has not been studied on the ground, and the present paper is concerned only with the Butana grass patterns.

Physical and Geological Setting

The Butana (Arabic—'belly'), an area of semi-arid clay plain, lies on the southern fringe of the Sahara in the central part bounded by the

rivers of the Blue Nile, the Main Nile, and the Atbara, and the Kassala-Sennar railway in the south (Fig. 1). The annual rainfall ranges from about 100 mm. in the north to about 400 mm. in the south, though it is very erratic and years occur in which there is practically no rainfall and very little vegetation grows. Generally, however, particularly in the south, there is a considerable growth of grasses, which remain standing throughout the year.

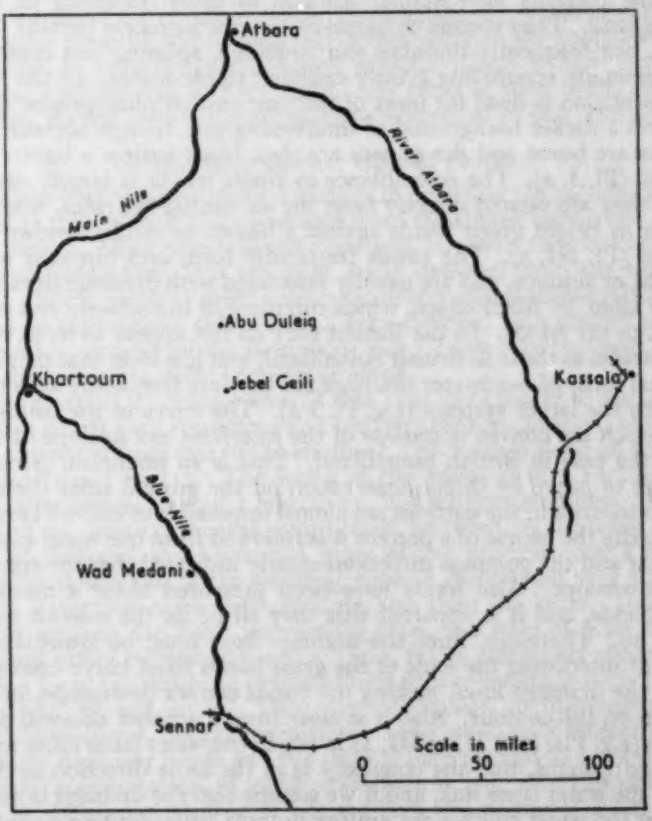


FIG. 1. The Butana.

The Butana has been geologically mapped and consists of Nubian Series to the west and north, and Basement Complex in the middle and to the south and east. Apart from the small isolated groups of rocky hills and low outcrops which jut out sharply from the plain, the solid geology is obscured by superficial deposits which are evidently the *in-situ* weathering products of the solid formations, and form two distinct soil groups, a red sand or loamy sand over the Nubian Series, and a

brown, rather heavy soil over the Basement rocks. The latter soils, locally called *fuda* and characterized by their loamy friable nature, are the only soils on which the grass patterns have been observed, and even on these the patterns are mostly restricted to the east central part of the Butana.

Aerial Observations

Observations from the air and studies of the aerial photographs show that the patterns have similar features to those occurring in British Somaliland. They consist of bands lying approximately parallel to each other, but frequently thinning and widening, splitting and combining, and generally resembling greatly enlarged ripple marks. In the Butana the vegetation is dead for most of the year and on photographs appears light on a darker background of intervening soil, though sometimes the grasses are burnt and the grasses are then black against a lighter background (Pl. I, A). The resemblance to ripple marks is largely dispelled when they are viewed directly from the air during the rains, when they appear as bright green bands against a brown or reddish-brown background (Pl. III, A). The bands frequently form arcs but may also be straight or sinuous, and are usually associated with drainage lines, called 'water lanes' by MacFadyen, which run more or less straight and at right angles to the bands. In the Butana they do not appear to be as regular and parallel as those in British Somaliland, and it is clear that they are an unusual form of headwater drainage for they are frequently seen to link up with the larger systems (e.g. Pl. I B). The curve of the bands form arcs which are convex *downslope* of the interfluve not upslope as is said to be the case in British Somaliland. This is an important point, and difficult to prove by direct observation on the ground since the course and boundaries of the patterns are almost impossible to follow. However, on one site the course of a pattern was followed from one water course to the next and the compass directions clearly indicated that the convexity was downslope. Also levels have been measured along a number of grass bands, and it is apparent that they all lie on the contour or very nearly so. Therefore, since the drainage lines must be lower than the adjacent interfluves the ends of the grass bands must curve upslope towards the drainage lines, making the bands convex downslope, in order to keep on the contour. Also it is clear from a number of aerial photographs (e.g. Pls. I, B; II, A; III, A) in which the water lanes unite to form drainage systems, that the convexity is in the same direction as that in which the water lanes link, and if we assume that the drainage is normal, i.e. that the water courses are uniting to form larger courses downslope, not splitting as in a delta, then the convexity is downslope also. This has been shown to be true in the example of Pl. II, B by ground examination, and that of Pl. I, B by examination in a Wild plotting machine.[1] But in Somaliland it appears that the water lanes can spread out to form small deltas, and the bands may cross these lanes (as they appear to do also at *x* in Pl. I, B of this paper), so that their convexity would be upslope while their position is still on the contour. This seems to be the case in several

[1] By Mr. P. E. T. Allen, Survey Dept. Sudan Government.

of the British Somaliland photographs shown, but in others the patterns are apparently on the interfluves and it is possible that the direction of the drainage may have been misinterpreted.

The association of the grass patterns with the drainage lines, as seen from the air, makes it apparent that the phenomenon is in some way connected with water action, but not with wind. The possibility of wind being a factor is discounted by the disposition of the patterns which may lie in several directions in a small area (Pl. III, A). In the northern Sudan the winds are regularly northerly for all the dry season, and southerly during the brief wet season, and farther north in the true desert the effect may be seen in the movement of sand which is in a southerly direction, forming seifs and barchans. Any effect of wind in the Butana, therefore, should be to produce patterns orientated in one direction.

Ground Observations: General Features

Some trouble was experienced initially in detecting the patterns on the ground as it is difficult to fix positions from the almost featureless plains of the Butana. Once observed and examined, however, they become easy to identify elsewhere, and are most easily detected from the top of a vehicle. Many patterns show a sharp boundary of tall grass against bare ground on the upslope side which is very striking, with shorter grasses tailing off irregularly on the downslope side. They occur on land which has a slight but generally perceptible slope.

Measurements by dumpy level (Table 1) at right angles to the lines of the grass bands gave consistent and uniform changes in level, and were fairly consistent from one site to another. The average slope on the sites measured was 1 in 217. The width of the bands is very variable, the range lying between about 1 and 20 m., but is very commonly between 8 and 12 m. Measurement is complicated, however, by the usual occurrence of flattened and blackened grass of the previous year's growth which lies downslope of the standing grass of the current year and may cover a wider but more indeterminate area than the latter. Including this old grass in the 'bare' intervening areas, the ratio of grass to bare measured varies between 0·9 and 4·7 to 1, but is commonly about 2 to 1 (Table 1), and the complete rhythmic unit or wavelength is fairly regular at between 30 and 40 m. Thus, by comparison to the examples in British Somaliland, the Butana patterns occur on slightly steeper slopes, they form narrower bands and the ratio of bare ground to grass is less.

Careful measurements of levels were made at 2-m. intervals across the bands to determine whether or not the land was higher or lower under the grass relative to the bare areas, as there was no difference perceptible to the eye. In spite of the irregularity of the soil surface under the grass which made measurement to less than 1 cm. uncertain, the rate of fall was remarkably consistent, and no change of level on the grass relative to the bare ground could be detected. Thus one possibility of the origin of the grass patterns, i.e. dune formation, was ruled out.

Although the patterns always occur on gently sloping ground, not all gently sloping ground in the Butana has grass patterns. Some has a patchy cover or, when more or less flat, a cover which is almost complete.

TABLE 1

Levels, Ratios, and Wavelengths

	Levels		*Ratio bare:grass*	*Wavelength*
	Along bands	*Across bands*		
Site Ia	1 in 2,000	1 in 300	..	..
Site Ib	..	1 in 280	2·2:1	32 m.
Site II	1 in 2,250	1 in 225	..	..
Site A	Slightly irregular. Max. variation in 120 m. = 10·5 cm.	1 in 121	0·9:1	38 m.
Site B	Same. Max. variation in 160 m. = 6·5 cm.	1 in 227	2·1:1	28 m.
Site C1	Same. Max. variation in 240 m. = 6 cm.	1 in 234	2·4:1	54 m.
Site C2	..	1 in 170	1·6:1	40 m.
Site A–C	..	1 in 162	4·7:1	35 m.
Averages	..	1 in 217	2·3:1	37 m.
Site G	No bands: cover nearly complete	1 in 580	..	..
Site H	No bands: cover nearly complete	1 in 513	..	..
Site J	No bands: cover patchy	1 in 500	..	..

Levels taken on three of these sites show that the slope was 1 in 500 or less (Table 1) and it would appear that there is a minimum slope of about 1 in 400, on less than which grass patterns do not develop. Conversely there must be a maximum slope above which grass patterns do not develop, but these have not been observed in the Butana where the slopes, except for the narrow aprons around jebels, are always less than 1 in 100. Observations indicated that there was a connexion between the angle of slope and the ratio of grass to bare ground, the ratio increasing with the increased slope. As yet, however, the measurements have not given any conclusive evidence of this.

Other causes of the phenomenon have been looked for in the soil, and over a period of two years regular visits have been made to the Butana to examine and sample the soil under the grass and bare ground, and also, when it appeared that the flora present might be significant in the formation of bands, a study of the amounts and distribution of the various plants was made.

The Soil

The soil surface is often strewn with large quartz pebbles, which may be as much as 5 in. across, and sometimes large angular boulders of igneous or metamorphic rock may occur, and it was at first thought that the underlying rock might not be far below the surface. If this were so, and the rock consisted of alternating strata of differing weatherability or chemical composition, so that soils of differing depths were formed, it could explain the formation of the grass patterns. Pit digging and augering to 6 ft. did not expose any solid or weathered rock or even any change of texture in the soil except for the top layer, so that, although it is probable that the rock does not lie very deep under the soil, it is unlikely that it is directly responsible for the rhythmic patterns.

Pits 4 ft. deep and 8 ft. long were dug across the upper junction of the vegetation and bare ground in order to examine the profile and any changes therein between the two ends. There was no difference between them. The profiles consisted of a mid-brown to grey-brown sandy loam/clay loam extending throughout their depth except that the top foot or so is slightly lighter in colour and contains more stones and coarse sand than the lower part. A typical profile is as follows:

	Thickness	
A Horizon	10–15 in.	Mid-brown loam to c.s. loam with quartz pebbles prominent; structure crumb to lenticular, few vertical cracks; no concretions; roots abundant (under both grass and bare ground): gradual transition to
B Horizon	60 in. plus.	Dark grey-brown clay loam, with occasional small quartz pebbles to 3 ft.; structure small lenticular, sometimes slickensided; concretions as small whitish granules; roots few ending at 3 ft.

The difference in texture in the A horizon appeared to be general, and is substantiated by mechanical analyses (by decantation, Sudan method) shown in Table 2. It will be seen that the clay content shows a distinct rise below about the 12-in. depth. On the unpatterned sites (E, F, H) which are almost flat, there is little or no difference in texture at the various depths. From this it would seem that there is lateral eluviation of clay particles through the top layer of the soils on the slopes. It cannot be due entirely to vertical eluviation as this would show in the flat as well as in the sloping areas.

The mechanical analyses do not reveal regular differences between the soil under grass from that under bare ground, so that another possible cause of the patterns, that of gilgai, appears on this evidence to be excluded. A number of other analyses was made, as follows: moisture, soluble salts (conductimetric method on a 1 to 5 soil : water ratio), sodium (method of Middleton, 1954, using 60 per cent. alcohol, 2 per cent. ammonium oxalate, and photoelectric measurement), pH (glass electrode, 1 to 2·5 soil : water ratio), nitrates (brucine method of Dickinson (1943)), organic carbon (Walkley-Black), organic nitrogen (Kjeldahl), and clay minerals. Except for moisture, the differences are generally small or absent, indicating that the grass bands are not permanently placed features of the landscape as suggested by MacFadyen, otherwise it would be expected, for example, that the organic nitrogen would be distinctly higher under the grass. It was obvious, on the other hand, even before any analyses were made, that the soil under the grass was moister than under bare ground, and was consistently moister long after the end of the rains and the growing season (Table 3). The implication of this was that more moisture was received under grass than under bare ground, and this was borne out later when the writer was fortunate enough to visit sites within a few days of the first rainstorm of the season. It was very clear that the extent of moisture penetration was much less

TABLE 2
Mechanical Analyses

	Site 1 (Bare)			*Site 2 (Grass)*			*Site C (Bare)*			*Site C (Grass)*			*Site A1 (Bare)*			*Site A1 (Grass)*		
Depth	*0–6″*	*6–12″*	*12–18″*	*0–6″*	*6–12″*	*12–18″*	*0–6″*	*6–12″*	*12–18″*	*0–6″*	*6–12″*	*12–18″*	*0–6″*	*6–12″*	*12–18″*	*0–6″*	*6–12″*	*12–18″*
S. & G.	..	..	..	..	..	..	5·0	4·0	3·6	3·0	2·2	2·7	3·8	4·8	4·0	6·7	4·2	3·6
C.S.	..	..	..	..	..	..	30·0	27·0	29·8	28·1	28·7	32·5	19·8	21·9	19·9	15·4	19·6	20·4
F.S.	..	..	..	..	..	..	16·1	15·5	14·9	14·0	14·7	15·3	22·0	19·0	11·2	20·0	19·8	19·8
Silt	11·5	9·3	8·6	11·2	13·5	11·3	9·1	11·5	4·7	23·4	14·0	10·1	21·6	17·0	22·8	24·0	19·4	19·6
Clay	46·2	51·4	57·8	46·6	51·0	55·8	40·0	45·5	48·2	32·8	39·2	43·2	32·8	37·9	42·1	33·5	39·0	38·5

	Site A2 (Grass)			*Site D (Bare)*			*Site D (Grass)*			*Site E (cont. cover)*			*Site F (Almost cont. cover)*				*Site H (Almost cont. cover)*		
Depth	*0–6″*	*12–18″*	*36–48″*	*0–6″*	*12–18″*	*36–48″*	*0–6″*	*12–18″*	*36–48″*	*0–6″*	*6–12″*	*12–18″*	*0–6″*	*6–12″*	*12–24″*	*24–36″*	*0–6″*	*12–18″*	*36–48″*
S. & G.	3·5	3·9	2·7	4·3	4·8	6·4	8·5	2·5	13·11	5·2	2·0	2·3	1·8	1·8	1·8	2·7	3·6	3·0	4·6
C.S.	39·4	32·4	28·6	7·9	9·7	11·5	8·3	11·2	8·0	7·8	6·5	7·3	8·8	10·8	9·7	9·5	6·1	6·1	5·9
F.S.	19·4	16·6	15·7	27·3	23·9	20·4	27·9	25·0	19·5	16·9	16·7	16·5	24·8	24·7	22·4	23·3	25·0	23·9	22·6
Silt	10·9	9·2	8·5	14·4	13·6	12·6	14·1	13·1	12·4	6·9	13·8	10·9	12·7	11·9	13·3	12·9	12·3	13·0	12·5
Clay	26·8	37·9	44·5	46·1	47·7	49·1	40·3	48·2	47·0	60·0	58·4	60·8	52·0	50·8	52·7	51·5	53·4	54·1	54·4

TABLE 3
Moisture (Per cent. Oven-dry Soil)

Depth (in.)	11 Nov. 1955				15 July 1956				8 Sept. 1956					
	Site 1		Site 2		Site C		Site B		Site A				Site D (pit)	
	Bare	Grass	Bare	Grass	Bare	Grass	Bare	Grass	Mid Bare	Fine Grass	Mid New	Mid Old	Bare End	Grass End
0–1	..	..	..	..	19·9	26·5	..	..	4·9	2·5	8·8	4·7	..	..
6	7·4	8·1	8·7	9·0	6·9	25·3	9·8	21·7	7·7	8·1	14·0	10·9	11·6	14·8
12	8·1	10·6	8·6	9·3	8·2	20·3	14·6	23·6	7·8	8·0	15·2	13·4	9·3	15·5
18	9·8	12·6	9·5	11·5	8·4	6·2	8·2	20·7	8·8	9·2	10·3	15·9	7·3	14·9
24	11·2	13·6	10·2	14·9	9·6	7·0	10·0	10·2	7·8	..	16·3	13·2	8·9	9·7
30	..	..	..	..	..	..	..	..	..	..	18·6	13·0	..	..

Depth (in.)	16 Oct. 1956								11 Dec. 1956				
	Site A			Site C			Site D		Site A				
	Bare	New	Old	Bare	New	Old	Bare	New	Mid Bare	Edge New	Mid New	Mid Old	Edge Old
6	8·2	12·6	12·4	13·4	14·8	13·1	11·6	13·7	6·0	8·0	6·8	9·3	5·0
12	15·5	14·2	10·6	10·8	19·7	11·8	10·8	16·2	..	8·8	6·7	13·4	10·2
18	15·4	16·0	13·9	10·0	18·4	12·6	9·0	13·0	8·7	10·1	11·7	13·2	11·2
24	..	16·3	14·2	..	15·1	13·6	..	11·3	..	..	..	..	..
30	..	12·6	..	..	12·7	..	..	..	..	..	..	..	..

Depth (in.)	6 & 7 Mar. 1957				4 Aug. 1957					21 Aug. 1957			29 Sept. 1957				
	Site A		Site D		Site D		Site C			Site C			Site C			Site A	
	Bare	Grass	Bare	Grass	Bare	Grass	Bare	Grass	Bare Dug	Bare	New Grass	Old Grass	Bare	New Grass	Old Grass	Bare	Grass Mat
0–1	..	..	..	..	5·9	8·2	3·9	8·7	..	9·2	14·7	19·8	..	..	..	8·7	11·6
6	6·1	4·2	5·9	5·7	9·0	15·5	7·9	17·9	8·6	8·9	15·5	21·0	5·5	8·2	19·0	8·9	12·3
12	7·4	11·5	8·0	7·8	7·1	16·8	8·1	21·6	5·7	7·5	19·7	21·1	4·3	8·7	15·2	8·2	8·9
18	8·7	11·6	9·3	11·1	7·2	24·4	9·6	22·5	..	..	..	..	..	8·7	21·9	..	..
24	8·6	11·5	10·0	11·3	7·2	11·3	8·8	13·4	..	..	..	..	..	9·9	29·5	..	..
30	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..

under bare ground than under grass, and amounted to 4–6 in. under the former, and 12–15 in. under the latter, the soil being quite dry beneath these levels. These differences were confirmed in the laboratory. Other measurements of moisture content made regularly since, show that the bare areas are consistently drier than the grassed areas throughout the year. The reason must be the increased intake of rainfall during the rainy season, and as the amount falling on any one of these sites must be approximately uniform, it means that the water must run off the bare areas and is restricted by the grass. This run-off must be very gentle as there is no sign of even minor gulleying or wash, and presumably the 'fetch' is too short for the water to develop any erosive power. Thus Nature appears to have adapted itself admirably to the climatic and topographic conditions—sowing in strips along the contour thus preventing erosion, and utilizing the limited water supply to the best advantage.

The results of estimations of soluble salts (Table 4) are all quite low, in most cases being less than 0·1 per cent. in any part of the top 2 ft. There is a gradual increase downwards over this depth, and on one site a rapid increase at lower levels, but not in the others. The differences between the soil under grass and that under bare ground are very slight and inconsistent, and are evidently not significant.

Estimations of sodium gave similar results (Table 5). The soils contain a few milliequivalents per cent., increasing gradually downwards, and there is no regular difference between the grassed and bare soil. Separate estimations of exchangeable sodium showed that the sodium was largely in this form, not as soluble sodium.

Estimations of pH (Table 6) indicate that this is generally slightly higher in the top foot in the bare areas as compared with the grassed areas, but the difference is not maintained lower in the profile. The difference in the top layer could be explained by the reduced leaching due to poor water penetration on the bare areas, and could develop over a short time, so that it does not imply that the grass patterns are static. The pH increases downwards in most cases, irrespective of the presence or absence of a grass cover, with a maximum at about 2 ft., after which there appears to be a slight decrease.

Nitrate estimations (Table 7) gave erratic results, but generally low. There is an increase with depth, usually slight in the top 2 ft. but very great lower in the profile in the few estimations made. The bare areas are consistently higher than the grassed areas, usually slightly, sometimes considerably. This could be explained by the fact that there is less uptake of nitrogen by the plants in the bare areas than in the grassed.

Estimations of organic carbon and nitrogen did not reveal any regular or substantial differences between the amounts under grass and under bare ground. For this reason it seems unlikely that the patterns are permanently placed features of the landscape.

Differing parent materials or differing history of development would probably be reflected in the types of clay materials present. However, X-ray analysis[1] of eight samples, at two levels, four under grass and

[1] Made at Rothamsted Experimental Station by kind permission of Dr. A. Muir.

TABLE 4

Soluble Salts (per cent.)

	July 1956		*Sept. 1957*					*Oct. 1956*		*Nov. 1955*				*Dec. 1957*			*Mar. 1957*			
	Site A		*Site C*			*Site A*		*Site A*		*Site I*		*Site II*		*Site D*		*Site A*	*Site C*		*Site D*	
Depth (in.)	*Bare*	*Grass*	*Bare*	*Old Grass*	*New Grass*	*Bare*	*Grass Mat*	*Bare*	*Grass*	*Bare*	*Grass*	*Bare*	*Grass*	*Bare*	*Grass*	*Grass*	*Bare*	*Grass*	*Bare*	*Grass*
0–6	0·09	0·12	0·05	0·05	0·06	0·05	0·05	0·08	0·08	0·06	0·05	0·10	0·07	0·05	0·05	0·04	0·07	0·06	0·06	0·08
6–12	0·07	0·12	0·04	0·05	0·05	0·05	0·05	0·08	0·08	0·06	0·06	0·10	0·07	0·11	0·07	0·02	0·08	0·07	0·09	0·08
12–18	0·08	0·09	..	0·06	0·06	..	..	0·08	0·08	0·07	0·07	0·13	0·10	0·09	0·08	0·05	0·09	0·09	0·10	0·08
18–24	0·08	0·08	..	0·07	0·09	..	..	0·08	0·08	0·12	0·13	0·18	0·17	0·14	0·13	0·05	0·11	0·15	0·12	0·12
24–36	..	..	..	..	..	..	..	..	..	..	..	..	..	0·25	0·25	0·05	..	..	..	..
36–48	..	..	..	..	..	..	..	..	..	..	..	..	..	0·36	0·44	0·07	..	..	..	..

TABLE 5

Sodium (m.e. per cent.) Total and Exchangeable

Depth (in.)	Site A (Total)		Site A (Exch.)		Site C (Total)			Site D (Total)		Site D (Exch.)	
	Bare	Grass	Bare	Grass	Bare	Old Grass	New Grass	Bare	Grass	Bare	Grass
0–6	0·6	0·4	0·5	0·3	1·5	1·0	0·8	1·1	0·3	0·8	0·2
6–12	1·1	0·8	0·9	0·6	0·9	2·7	1·5	3·8	2·5	2·9	2·3
12–18	1·5	1·7	1·0	1·3	..	4·9	3·3	5·5	4·8	5·1	4·7
18–24	2·5	1·9	1·8	1·4	..	3·5	5·7	7·3	6·8	6·3	6·2
36–48	..	..	..	..	..	..	..	8·3	7·8	7·2	6·4
48–60	..	..	..	..	..	..	..	8·3	7·1	7·5	6·3

TABLE 6

pH

Depth (in.)	July 1956		4 Aug. 1957				Sept. 1957			Oct. 1956		Dec. 1957		Mar. 1957			
	Site A		Site D		Site C		Site C			Site A		Site D		Site C		Site D	
	Bare	Grass	Bare	Grass	Bare	Grass	Bare	Old Grass	New Grass	Bare	Grass	Bare	Grass	Bare	Grass	Bare	Grass
0–6	7·7	7·8	8·0	8·0	8·0	7·8	8·0	7·8	7·9	7·8	7·7	8·5	8·0	7·8	8·2	8·1	7·7
6–12	7·8	7·8	8·4	8·0	8·2	7·9	8·1	8·0	7·9	7·8	7·8	8·6	8·5	8·5	8·3	8·4	8·2
12–18	7·8	7·8	8·3	8·3	8·2	8·2	..	8·1	8·3	7·9	7·8	8·8	8·7	8·7	8·3	8·4	8·4
18–24	8·0	8·0	8·4	8·3	8·4	8·2	..	8·2	8·2	8·0	8·0	8·9	8·6	8·5	8·1	8·7	8·5
24–36	..	..	..	..	..	..	..	..	..	..	..	8·3	8·3	..	..	..	..
36–48	..	..	..	..	..	..	..	..	..	..	..	8·2	8·1	..	..	..	..

TABLE 7
Nitrate Nitrogen (p.p.m.)

Depth (in.)	July 1956		4 Aug. 1957				21 Aug. 1957			Sept. 1957			Dec. 1957		Mar. 1957	
	Site A		Site C		Site D		Site C			Site C			Site D		Site A	
	Bare	Grass	Bare	Grass	Bare	Grass	Bare	New Grass	Old Grass	Bare	New Grass	Old Grass	Bare	Grass	Bare	Grass
0–6	2·9	1·7	13·0	12·4	12·0	8·5	10·5	7·5	6·5	9·4	2·6	9·4	4·0	2·6	1·4	0·6
6–12	2·0	1·3	7·4	5·8	10·0	7·5	32·0	7·0	7·5	5·2	2·2	3·8	70·5	3·8	2·8	0·8
12–18	1·7	1·3	10·4	4·8	16·5	6·5	..	..	..	..	2·0	2·9	22·0	3·8	1·0	1·3
18–24	2·0	1·7	19·6	10·0	22·0	11·0	..	..	..	..	2·2	2·6	72·0	50·0	1·4	1·4
36–48	..	..	..	..	..	..	..	..	..	..	..	..	117·5	125·0	..	..
48–60	..	..	..	..	..	..	..	..	..	..	..	..	130·0	155·0	..	..

four under bare ground, showed that they consist of at least 75 per cent. montmorillonite, with some chlorite, and doubtful kaolin, but there is no readily detectable difference between any of them. It is improbable therefore that any genetic difference can be the cause of the patterning.

Although no differences in profile could be detected, there is a distinct difference between the soil *surface* of the bare ground and that under grass. The bare ground is smooth and the surface broken only by shallow reticulate cracks extending a centimetre or so into the ground. Under grass the surface is either strongly cracked or pitted with potholes of various sizes and more or less filled in. These potholes evidently form each year at the beginning of the rains, for new ones were observed after the first rainfall, most of them appearing on the bare ground just upslope of the boundary of the dead grass (Pl. IV, A). They were obviously fresh, and formed by internal collapse and not due to any extraction of soil such as might be caused by a burrowing animal (Pl. IV, B). At the surface the holes may be only a few inches across, but they widen immediately below the surface forming an approximately ovoid shape and extending downwards to an average depth of about 9 in., the depth ranging between 5 and 14 in. The formation of the arched roof appears to be due to the binding effect of the many roots, the ends of which can be seen on the underside of the arches. These do not last long as subsequent rains cause them to collapse, and with rain wash and perhaps animal treading, the holes partially fill in.

An attempt to ascertain the shape of the potholes was made by pouring plaster of paris into them to obtain their casts. These showed the increase of width below the surface, even though the casts were taken long after the rains, but it appears that the subsurface shape is less rounded than at the surface. The casts also showed the presence of one or more small holes running off horizontally from them, approximately round, 1–2 in. across, and keeping a constant depth beneath the ground (Pl. IV, C). Some disappear after a few feet but others have been traced for over 2 m. without coming to the end of them. They are possibly burrows of mice or other small animals, but the frequency makes this unlikely.

The positioning of the new holes is surprisingly regular. Apart from a few holes found in lanes in the patterns—probably animal tracks—they were nearly all concentrated on the bare ground within a metre of the upslope edge of the grass (Pl. IV, A). During the ensuing rainy season the potholes became enveloped by new grass, the front thus advancing slightly upslope from the previous season's position. Measurement of the moisture content of the soil through the season showed that the line of deep penetration of water advanced upslope during the rains, in step with the growth of vegetation and evidently slightly preceding it. A pit dug across a pothole after the first rainfall showed that the soil was moist around and immediately beneath the hole, but that $\frac{1}{2}$ m. away the soil was dry almost to the surface. The implication of this is that the holes form first and then become centres for water accumulation, and later the growth of vegetation. It was thought at first that the potholes, which elsewhere appear to form in places where the moisture status is relatively high, were directly due to wet conditions, but if so it would be

expected that they would form under last season's grass where the depth of penetration and the amount of moisture is initially greatest. Moreover the small patches of grass occurring in the 'bare' areas invariably have one or more potholes in them, and in these cases it is not possible to decide whether the hole is a consequence of the grass growth or vice versa.

In addition to the potholes there is much cracking of the soil which, under grass, may be as much as 2 ft. deep though is usually only a few inches. In the forefront the cracking is more or less continuous and rather irregular in direction but with a definite trend parallel with the grass front, as if there were some gravitational pull opening the soil at its weakest point, i.e. where it has become moist and is not bound by vegetation. A further complication is that under some grass patterns (those consisting dominantly of *Cymbopogon nervatus*) there are no potholes, though strong cracks are always present. And elsewhere, in places where *Cymbopogon nervatus* is less dominant, elongated holes resembling both potholes and cracks have been observed.

In 1957 an attempt was made to imitate the soil conditions existing on the grassed areas by digging over roughly the surface of the bare ground on three sites, the object being to encourage water penetration and plant growth. These were observed during and after the rains. The result was that the patches became washed over and almost as smooth as the undisturbed bare ground, and no vegetation developed. Moisture measurement in a dug-over patch showed that there was very little difference between it and the bare ground (Table 3. Site C, 4 Aug. 1957).

During the same period observations were made on mats which were made of dead grass and fixed to the surface of the bare ground with wire stakes, the object being to see if these would assist in the penetration of water and so encourage grass growth. During the subsequent rainstorms the winds were evidently very violent as one mat was completely shredded and blown away and half of the other disappeared in the same way. The remainder collected sufficient dust and sand—some very coarse—to be firmly anchored in the ground by the end of the rains. From this a few grass shoots appeared, not in abundance but more frequently than on the bare ground. Moisture measurement under this and the adjacent bare ground showed that penetration in the top 6 in. was distinctly better under the mat (Table 3. Site A, Sept. 1957) but not comparable to that under rooted vegetation. From this it seems probable that the surface vegetation acts as a trap for dust, sand, and plant debris including seeds blown by the pre-rainstorm winds, and later for water as it moves over bare ground.

A further observation which may be significant in this connexion is that no vegetation has developed in the pits dug in the grassed areas or on the spoil from them even after two seasons' rain, though the water penetration in the pits has been good.

Vegetation

The observation that the type of vegetation appears to be associated with differences in the soil surface led to a closer study of the vegetation present.

The 'bare' areas are not usually completely bare. Throughout the year they have small grass patches which may be isolated and more or less round, or more usually slightly elongated along the contour as if they were incipient grass bands. Indeed, all stages from small elongated patches to continuous bands may be seen. Also, there is usually a thinly scattered but even cover of stunted grasses. During the growing period many small flowering plants appear on these areas. They are very ephemeral, and when they die their remains quickly disappear and very little vegetation except grass is seen during the dry season.

The grasses of the vegetation bands remain standing and retain a yellow-brown colour throughout the dry season. During this period it was noticed that there was often some older grass, flattened and blackened, on the downslope side of the current season's grass, both in it and beyond it, and this was evidently the remains of the previous season's growth. This was confirmed when the next season's vegetation was seen to appear on the upslope side of the standing dead grass, and in the early part of the rains, three seasons' grass could be detected lying in succession along the contour. Later, the previous season's grass became blackened and flattened by the rain and it was then difficult to distinguish it from the two-year-old grass. It seems fairly certain, therefore, that there is a slow annual migration of the bands upslope, the dead vegetation being left behind and gradually disappearing. The amount of annual advance appears to vary from site to site. On those sites where pits had been dug across the boundary of the grass and bare areas, the amount of encroachment upslope by the grass could be measured with some accuracy, and was found to vary from 1 to 5 ft. In the next season (1957) attempts to measure this advance more exactly were made by placing iron stakes linked by wire along a short stretch of grass front. Unfortunately, the rains were late and poor and the new grass had a very limited growth. Most of it—often only a few feet wide—was confined to within the old grass front but there was some slight advance upslope amounting to a maximum of about 2 ft. On another site where growth had been much better the advance of the front, based on the position of a pit dug the previous year, was from 3 to 5 ft. This migration would explain the lack of difference in soil properties and constituents between the grassed and bare areas. It would also explain the relative abundance of roots occurring under the bare ground which cannot be derived from the thin vegetation immediately above them, but must be survivals of the time when the ground was part of a vegetation band.

Although evidence for this upslope migration has been seen on a number of sites, on some there is no sign of any grass of the previous season. These are all areas in which *Cymbopogon nervatus* is the dominant grass, and in which potholes are generally absent. At least some of these areas were seen to be bare of vegetation in the previous season, and it is possible that *Cymbopogon* is a pioneer grass which invades an area made bare by lack of rain or through the burning of the previous season's vegetation. Moisture measurements suggest that the depth of penetration of water under *Cymbopogon* is less than under *Aristida*, another dominant grass, so that the former might be able to establish

itself first, and later give way to other grasses when the moisture content of the soil could be built up by its own roots and stems.

A study of the vegetation during and after the rains revealed that, although a few species of grass are strongly dominant, there were many other grasses and herbaceous plants, and some had restricted positions in the patterns. The plants identified were as follows:

Grasses

Dominant:
- *Aristida* spp., chiefly *funiculata.*
- *Sehima ischaemoides.*
- *Schoenfeldtia gracilis.*
- *Cymbopogon nervatus.*

Chloris virgata.
Cymbopogon proximus.
Echinochloa colona.
Eragrostis sp.

Herbaceous plants

Dominant:
- *Cucumis melo* var. *agrestis.*
- *Crotalaria senegalensis.*
- *Ipomea cordofana.*

Solanum dubium
Tephrosia gracilipos
Tephrosia uniflora
Blepharis sp.
Digera alterniflora
Chrysanthellum americanum.
Forsetia longiliqua.
Cyperus rotundus.

On a number of sites *Schoenfeldtia–Aristida–Sehima* were strongly dominant, and these were always found with the remains of the previous season's grass which appeared to be of the same species. The distribution of the species is remarkable in that the *Schoenfeldtia* occurs as an almost pure stand adjoining the others on the upslope side of the band. *Schoenfeldtia* is smaller than the others and forms a short pale fringe to the tall dark green main front formed by *Aristida–Sehima.* This junction was traced over considerable distances on several sites, and later was used for levelling along the bands as there was no doubt as to its position, as was sometimes the case when using the edge of the grass band. This disposition of the species suggests that the suitable conditions for their growth must be very critical. Observations indicate that *Schoenfeldtia* has a lower moisture requirement than the other dominant grasses and that in the early part of the growing season the favourable moisture conditions of the vegetation band and its immediate forefront enable these to get away fast and prevent the growth of *Schoenfeldtia,* which, however, develops later in the forefront of the other grasses where there is not sufficient moisture for them to grow.

On some other sites the dominant grass is the prominent bunchy *Cymbopogon nervatus,* sometimes occurring as almost pure stands, but more often associated with *Aristida funiculata.* In these bands there is no distinct junction between the two grasses, but the *Cymbopogon* is

concentrated towards the front and *Aristida* to the rear. A closer study of the distribution of species made on a *Cymbopogon* site in the following year showed that several subordinate plants were present in a fairly regular order. *Cymbopogon* occurred throughout but was most dominant in the new front. With it in the front was the white-flowered legume *Tephrosia* sp. followed by *Schoenfeldtia gracilis*, followed by *Aristida* sp. with a little *Chloris virgata*. As in the previous year there was no dead grass derived from *Cymbopogon*, but a little remained from *Schoenfeldtia* and probably *Aristida*.

Herbaceous plants are prominent during the rains, but soon wither and disappear, and only a few species are to be seen during the dry season. Under the new grass they are scarce, but they may be abundant in the old grass and the 'bare' areas. In the *Schoenfeldtia–Aristida* patterns, the herbs, especially *Cucumis*, *Crotalaria*, and *Ipomea*, are concentrated in the old grass areas behind the new grass front, while the 'bare' areas consist mostly of stunted grasses of the same species as occur in the bands. The herbs are most abundant, however, in the *Cymbopogon–Aristida* areas where they make a fairly close cover to the whole of the 'bare' areas, and consist largely of the yellow *Crotalaria* and the blue *Blepharis*. The difference in distribution of the herbs and the grasses appears to be due to the lower moisture requirement of the former and their inability to compete for light with the tall grasses. They mature rapidly as do the grasses where the moisture supply is short. Towards the end of the growing season the only part of the areas remaining green is the line of tallest growth towards the front of the new grass areas. Another factor is probably the nitrogen supply, for among the herbs there are many legumes. Analyses of the nitrate content in various parts of sites show (Table 7) that the amounts are generally low, and the lowest appears to be under the grass areas, especially at the end of the growing season. If this deficiency continues until the next rains it is understandable that grasses would not flourish on the areas of last season's growth, even when moisture conditions are favourable, though legumes might make good use of them. The migration of the grasses upslope may be due, therefore, to a need for more nitrogen. A further possibility is that the dead grasses produce inhibitors which restrict growth in the subsequent season. Many desert plants according to Went (1953) contain growth-inhibiting substances, and the fact that mulching in dry climates can have a depressing effect on crop growth is explained by the failure of the scanty rains to leach out the inhibitors in the mulch. This explanation does not seem very likely, however, as it would not explain the concentration of new grass growth on the upslope side of the bands and not on the downslope side.

The Origin of the Grass Patterns

The results of these investigations show that the grass patterns are associated with certain climatic, topographic, and soil features, without providing any sure evidence of their mode of origin, except to show that water is a factor but not wind. The role of the associated potholes, though apparently of some importance, is not that of initiating the

growth of grass in bands, for some bands occur without potholes. The difference of soil surface suggests the possibility of a connexion with *gilgai*. According to Hallsworth *et al.* (1955) the features of gilgai relief include some rise and fall between the puff and shelf portions, deep cracking in the latter coupled with infilling from the surface and consequent difference in profile and properties between each part. But though the cracked and potholed surface under grass has some resemblance to the shelf areas there is little else to connect the phenomenon with gilgai. There is no rhythmic rise or fall between the bare and grassed bands, no apparent soil profile difference, and very little difference in soil properties, notably in mechanical composition and amounts of exchangeable sodium. Also gilgai occurs on a greater variety of slope or even on horizontal ground, and does not normally exhibit potholes, though these have been recorded in Nyasaland. There is a superficial resemblance to the contour trench formations described by McElroy (1951) in New South Wales, but these have trench-like depressions alternating with higher ground and the patterns are on a smaller scale. The only other gilgai formation resembling the grass patterns is the wavy form, but this runs commonly down slope, not along the contour. Moreover, accounts of gilgai lay stress on topographic and soil differences, with little mention of vegetational differences. Where these occur it appears that the growth may be restricted to the shelf in stony gilgai in Australia (Hallsworth) or concentrated on the puff in normal gilgai in Kenya (Stephen *et al.*, 1956).

On the other hand, in the shelf portions in Australia there is an increase of clay content with depth, as is the case with the grass-patterned land as a whole. It seems possible, therefore, that this phenomenon may be an incipient form of gilgai which requires for its development a clay profile which is lighter textured in the top layer than at depth. Such soils could be produced by the eluviation of fine particles either vertically or laterally. In dry climates it is unlikely that much vertical eluviation will occur, and in the Butana the uniform composition of the soil profile on more or less flat ground is evidence that this is so. Lateral eluviation of fine particles on slopes has been described in both weathered geological material (Stheeman, 1932; Ruxton and Berry, 1957) as well as in soils (e.g. Robinson, 1936; Charter, 1949), though, to the writer's knowledge, not on slopes as gentle as 1 in 200. Subsurface eluviation of fine materials has also been used to explain the formation of gullies by Rubey (1928), and Buckman and Cockfield (1950). The formation of these gullies is preceded by sink holes of 50 to 100 ft. across and up to 50 ft. deep, and they develop in silty materials. It is possible that the potholes in the grass patterns, though much smaller, may develop in a similar way. Most water will collect in the upper front of the grass bands and most fine earth will be eluviated there, with the eventual collapse of the surface at points where the process has been most rapid. If this is so, then the potholes and cracks are a result of the grass bands, not the cause.

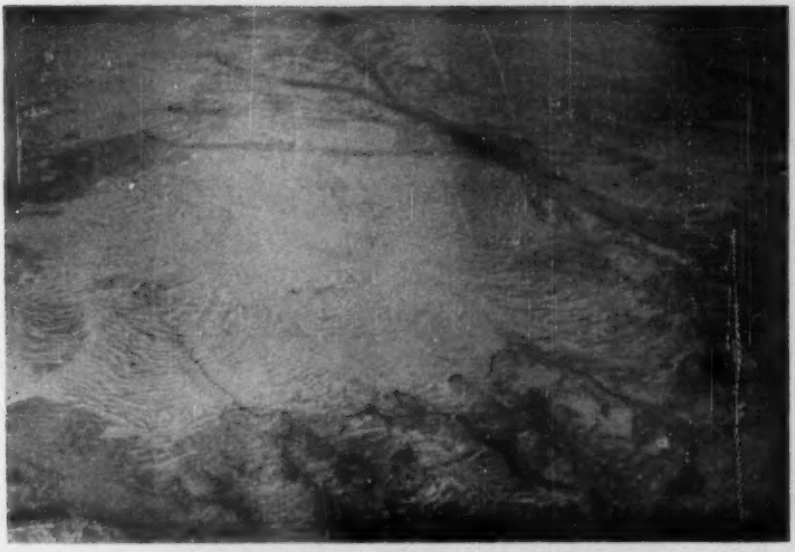
Vegetation patterns have been described by Ives (1946) and Harper (1957), both from arid and semi-arid regions. The bands of sage

described by Ives are on wind-formed arcuate desert sand ripples 10 to 36 in. high occurring at 10 to 50 ft. intervals with intervening saline clay which is temporarily submerged by water during rains. Here the banding is related to a topographical rhythm and evidently different in origin from that of the grass patterns. The ring growths described by Harper have a similarity to the grass patterns in consisting of an area of dead grass inside a circle of growing grass. They occur at high elevations, mostly on sandy soils, and the few chemical analyses made suggest that there may be a nitrogen deficiency and perhaps also a phosphate deficiency, but there is no information about the slope or the mechanical composition of the soil profile. As with the grass patterns, the movement will not explain the original positioning of the vegetation. In the case of the grass patterns this must in some way be related to the slope of the ground. Two possibilities are suggested. The formation of soil cracking parallel with the grass bands may be due to a gravitational pull resulting in alternate compression and expansion of soil in rhythmic form without the surface being corrugated. The expanded parts would permit greater depth of water penetration and so more favourable conditions of plant growth. Or, as was suggested by MacFadyen, the cause might be purely superficial, the dead debris of vegetation forming 'strand lines' in which seeds are concentrated, though 'strand line' is not a suitable word as the debris could not be left by a retreating water level. That dead vegetation can be washed into lines like ripple marks has been observed by the writer on sloping ground in several places in the Sudan. These are much smaller than the grass bands, but it seems possible that rhythmic deposition of this kind might occur on a large scale, a gentle sheet-flow of water developing an attenuated wave form of great length and small amplitude, with deposition of plant debris concentrating beneath the crests. There is no difficulty in the Butana in understanding how this kind of deposition could be imposed on a pre-existing vegetation, for there occur years in which much of the Butana, because of poor rains, is almost bare of vegetation. Also burning often occurs, and the charred remains after the fires are soon blown away leaving little sign of vegetation.

At present there is still insufficient evidence to draw any conclusions as to the origin of the grass patterns. It would probably be of value to observe the action of rain as it is falling on these areas, to see what run-off there is and whether debris is moved by it, and to see potholes in the process of forming. This is more difficult than might be imagined, as there is no certainty on trekking into the Butana that rain will fall for a number of weeks or, if it does, that it will be possible to return through the morass of mud that the *fuda* soils become after rain has fallen.

Acknowledgements

The author is indebted to the following members of the Faculty of Agriculture, University of Khartoum: Dr. M. A. Nour and Mr. R. C. Seeley for identification of plants, the latter also for interest and advice on the work, and Osman Eff. Siddik for carrying out analyses. Thanks are also due to Sayyed C. Hantoun, director, Survey Dept., Sudan



A. Grass patterns: form in relation to drainage

B. Grass patterns: form in relation to drainage. Note bands crossing a wadi at x

G. A. WORRALL—PLATE I

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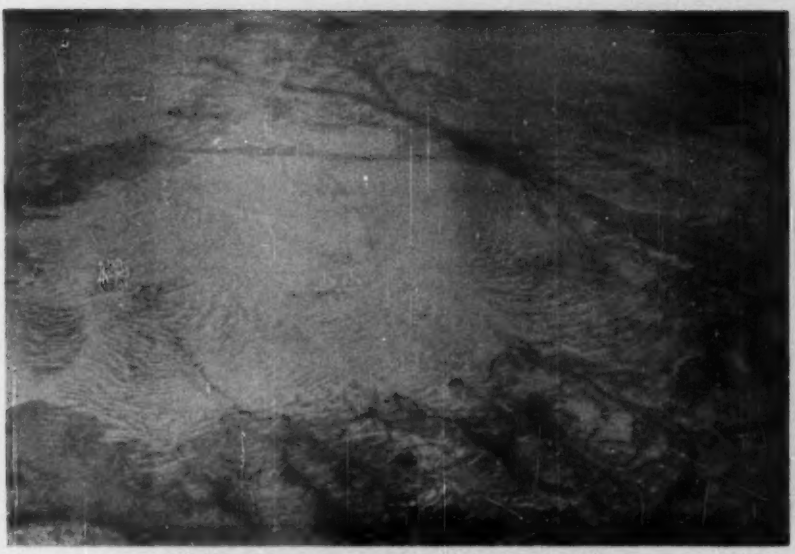


A. Grass patterns: form in relation to drainage

B. Grass patterns: form in relation to drainage. Note bands crossing a wadi at x

G. A. WORRALL—PLATE I

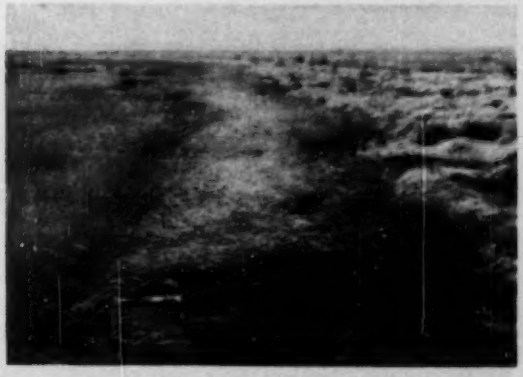
A. Grass patterns: burnt and unburnt

B. Grass patterns: form in relation to drainage

G. A. WORRALL—PLATE II

A. Grass patterns: multidirectional disposition. Grass here shows dark because it is green

B. Grass band and bare ground. The upslope side is to the right. Note the patchy 'bare' ground



C. Grass band and bare ground, showing dark new grass in the centre and old grass showing light to the right

A. Forefront of grass band, showing soil surface, potholes, and reticulate cracking

B. New potholes with evidence of formation due to collapse

C. Plaster cast of pothole showing form and lateral tunnels

G. A. WORRALL—PLATE IV

Govt., and Mr. P. E. T. Allen, Aerial Survey Section, for provision of photographs, some of which (Pls. I and II) are reproduced here, and to Mr. T. Hodge for access to his findings on the same phenomenon in British Somaliland.

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NOTES ON WEATHERING ZONES AND SOILS ON GRANITIC ROCKS IN TWO TROPICAL REGIONS

LEONARD BERRY

(*Department of Geography, University of Khartoum*)

AND

BRYAN P. RUXTON

(*Shrewton, England*)

WITH ONE PLATE

Summary

In both Hong Kong and the Sudan weathered granitic rock between the soil and the fresh bedrock can be differentiated into distinct weathering zones which often form a characteristic weathering profile.

Weathering profile formation and erosion are most active on concave faceted hillslopes. On footslopes, valley-side strips, pediments, and plains active soil-profile formation occurs above complete or truncated weathering profiles.

A clear distinction between soils and weathering profiles is a pre-requisite to an understanding of landform development and soil patterns in tropical regions.

I. *Introduction*

In the semi-arid and humid tropics chemical weathering of granitic rocks may proceed rapidly beneath the surface. Under suitable conditions a thick cover (30 to over 300 ft.) of weathering debris is formed *in situ* over the fresh solid bedrock. The weathering profile so formed has been defined as 'the expression of the sequence of changes necessary to bring the fresh bedrock into equilibrium with the near-surface environment' (Ruxton and Berry, 1957, p. 1267).

Weathering profiles at the foot of concave hillslopes on granite in Hong Kong can generally be divided into four zones (ibid., fig. 2) approximately parallel with the ground surface. A structureless mass of reddish-brown sandy clay (Zone I) overlies a pallid silty sand with the structure of the parent granite preserved and a subordinate content of corestones (Zone II). Beneath this, Zone III, with dominant corestones and subordinate debris, rests on weathered bedrock (Zone IV).

At a certain stage in the development of these zones, partly dependent on surface slope and vegetation cover, migration of the surface material becomes significant. Most soils are developed on this surface veneer of migratory debris though some may extend downwards into the uppermost part of the weathering profile. In this paper the soil is considered as 'a modification of any part of the weathering profile which occurs near or at the ground surface' (ibid., p. 1268).

The *Soil Survey Manual* (1951, p. 8) of the United States Department of Agriculture states that 'soil is the collection of natural bodies occupying portions of the earth's surface that support plants and that have properties due to the integrated effect of climate and living matter, acting upon parent materials, as conditioned by relief, over periods of

time'. The modification of the weathering profile to form soil is due to the effect of living matter and surface influences (wetting and drying, strong insolation, &c.). The soil profile 'includes the collection of all genetic horizons . . . and the parent material or other layers beneath the solum that influence the genesis and behaviour of the soil' (ibid., p. 173).

When a soil profile is formed on a thick layer of migratory or transported material which overlies a weathering profile on solid rock, distinction between the two profiles is easy (Fig. 1). But when the soil forms

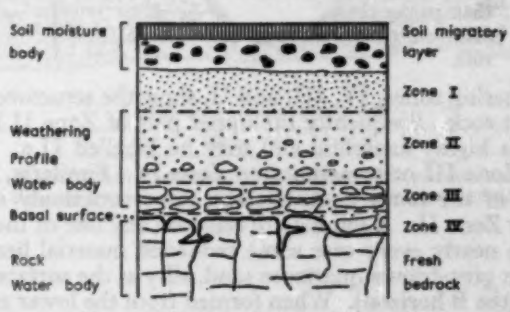


FIG. 1. The complete regolith profile.

directly on sedentary weathering debris, exact distinction may be difficult. If the weathering profile shows a clear division into zones, it is the upper zone on which the soil is formed.

It is said that the pedologist seldom looks 'far enough down' or the geologist 'far enough up'. The lack of recognition and study of weathering profiles as distinct from soil profiles appears to justify this statement. The purpose of this paper is to demonstrate this distinction by citing examples on granitic rocks from Hong Kong and the Sudan.

Neither author is a pedologist and we are grateful to Dr. G. A. Worrall for his keen scrutiny of this paper and his many helpful suggestions.

II. *Examples*

(*a*) *Weathering zones and soils in Hong Kong*

(i) *General.* Hong Kong experiences a South China monsoonal climate, 75 per cent. of the annual rainfall occurring in the summer months (June to September). There is a pronounced dry period in winter causing a considerable annual fluctuation in watertable level. Temperatures in July average 82° F. with high humidity and in winter frost is very rarely recorded.

The area is generally in a sub-mature stage of dissection but many localities show evidence of limited former gently sloping surfaces. The former vegetation cover has been completely removed and was probably of the rain forest type. Coarse grass, bare ground, and scattered scrub now prevail.

(ii) *Profile characteristics.* In many parts of Hong Kong the granite is

weathered to Zone II more than 100 ft. below the ground surface and a typical vertical section is as follows:

Thickness	*Description*	*Name*	*Type*
3–10 ft.	Grey-brown silty sand	A horizon	Soil or Solum
	Grey-brown clayey sand	B horizon	
30 ft.	Reddish-brown clayey sand	Zone I	Weathering profile
100 ft.	Pale silty sand, corestones less than 50 per cent.	Zone II	
25 ft.	Coarse debris, corestones more than 50 per cent.	Zone III	
25 ft.	Massive slightly weathered bedrock	Zone IV	

The weathering zones, IV, III, and II, show the structure and texture of the parent rock. Frequently the upper part of Zone II has no corestones and is highly kaolinitic and may be labelled II *a*. It may rest directly on Zone III or sometimes on Zone IV. Similarly, Zone I may rest on any of the lower zones though most commonly it is directly underlain by Zone II. A soil may develop on any one of the weathering zones and in nearly every case some reddened material lies beneath it. It is usually a grey-brown quartzose sand, silty at the surface, and clayey underneath (the B horizon). When formed from the lower zones it has a moderate content of macroscopic orthoclase and minor black biotite.

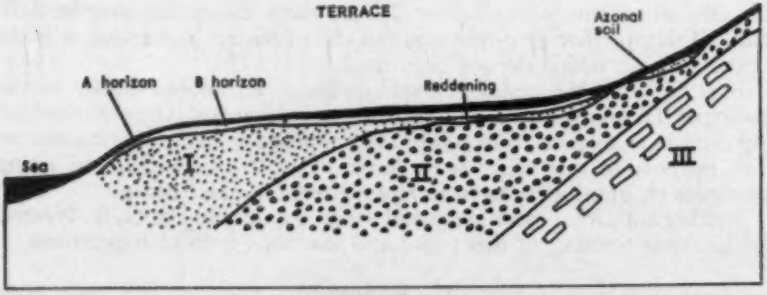


FIG. 2. The terrace at Lai Chi Kok, Hong Kong, showing the truncated upper zones of a complete weathering profile on granite and the overlying soil resting unconformably upon them.

(iii) *Disconformities.* At Lai Chi Kok (Fig. 2) a wave-cut terrace transects the upper zones of a mature weathering profile. The soils have since been developed on both Zones I and II of the weathering profile. The form of the latter is still adapted to the pre-terrace surface, though a patchy reddened mass beneath the soil probably represents post-terrace weathering.

Disconformities between soils and weathering profiles are also found on the two main types of slope in the Colony. Convex slopes occur when a complete weathering profile, formed on a gently sloping surface, has been dissected. On the hilltop the soils form on Zone I, on the steeper sides on Zone II, and in the valleys on slopewash, alluvium, or on the

lower zones (Fig. 3, Pl. I, *a*). Concave slopes with rocky buttresses or crests of solid rock (Zone IV) show the opposite sequence with soils resting on successively higher zones downslope. On the lower part of concave slopes the migratory layer thickens and the soil profile may be completely separated from the underlying weathering profile (Fig. 4).

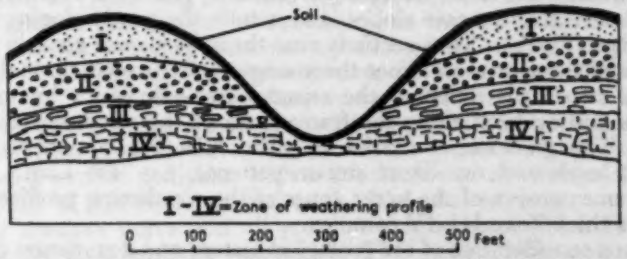


FIG. 3. A convex hill on granite in Hong Kong with sub-horizontal zones of a dissected weathering profile and the overlying migrating soil.

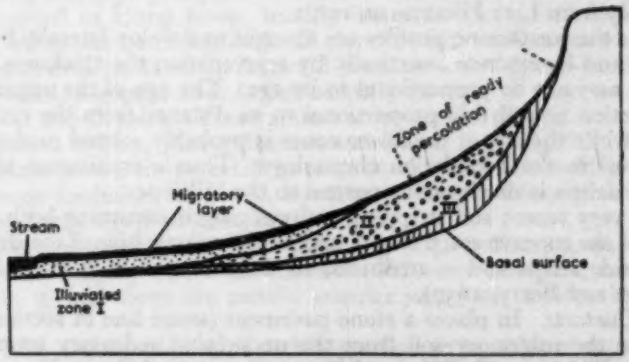


FIG. 4. A concave hillslope on granite in Hong Kong showing the form of the weathering profile and overlying migratory debris with soil.

On many such slopes with angles of 7–32° fans of granite boulders and clayey debris may occur up to 50 ft. thick, and here too the fan is parent material for any soil profile formed upon it.

The soil catena[1] (*U.S.D.A. Soil Survey Manual*, 1951, p. 160) which develops in these cases is not only a function of drainage and slope but also of the state of the weathered debris. Stephens (1946) also recognized individual soil types developed on the different zones of a dissected laterite profile (a weathering profile) in Australia.

In many instances the physical properties of the soils are quite different from those of the underlying weathering profiles and these differences are reflected in the type and effect of erosion on each. The soil, with its

[1] The term soil catena is used here to denote soil series of one soil zone which are developed ultimately from similar parent material, e.g. granite.

high content of colloidal material, tends to be removed by rainwash, creep, and slip, while the upper weathering zones are first affected by mechanical eluviation (Ruxton, 1958*a*) and then by catastrophic gullying. It seems possible that several soil covers can be formed and later removed during the degradation of one thick mass of Zone I debris.

(iv) *Erosion and time.* Complete weathering profiles are formed at the foot of retreating concave slopes, and mantle the gently sloping valley-side strips (Fig. 4). Thus sections near the axial stream courses are the oldest and those at the hillfoot the youngest. Rejuvenation of the axial streams causes dissection of the raised valley-side strips by tributary streams cutting back along the frameworks of the structural compartments. This gives rise to a series of convex hills (Fig. 3) with accordant summit levels and rectilinear stream patterns, e.g. Tai Lam. It also causes an extension of the lower zones of the weathering profiles giving rise to a thick Zone III–IV complex.

From a consideration of the geological history and denudation chronology of the Colony (Ruxton, 1958*b*; Berry, 1956) the commencement of weathering on the granite was probably post Mid-Tertiary and the development of most of the thick weathering profiles currently exposed probably from Late Pliocene onwards.

Since the weathering profiles are thought to develop laterally by slope retreat and be extended vertically by rejuvenation the thickness of any section may not be proportional to its age. The age of the upper zones in a section is probably proportional to its distance from the retreating scarp, while the age of the lower zones is probably related to the stages of revival in the denudation chronology. Thus a continuous sheet of Zone I debris is diachronous normal to the hillslope.

The very recent soil stripping and gullying is occurring both on the spurs of the concave scarp slopes, and on the convex hills of the dissected valley-side strips and is attributed to deforestation in historical times (Ruxton and Berry, 1957).

(v) *Contacts.* In places a stone pavement (stone line in section) may separate the migratory soil from the underlying sedentary weathering profile. This is well illustrated on small convex hills in Hong Kong (Pl. I, *a*). This stone pavement is interpreted as forming the base of the layer of more rapidly migrating material and is derived from the break-up of numerous quartz veins which cut the granite debris.

Kellogg and Davol (1949, pp. 9, 47) and Ruhe (1956, pp. 26–27) recognized a stone line in sections on the plains of the Belgian Congo separating upper migratory or transported material, on which the soils were formed, from the lower sedentary weathered rock. If no stone line occurs the separation of the migratory layer and the weathering profile can sometimes be made by examination of the heavy mineral fractions.

If the bedrock is homogeneous and yields no coarse (e.g. quartz) fragments in the uppermost zones of weathering (see Pl. I, *c*) it is difficult to decide the contact between soil and weathering profile. In this case the horizontal contact between Zones I and II is very sharp and is oblique to the present sloping ground surface. Soil formation has developed on the parent Zone I of the weathering profile, and fresh

solid bedrock at the base of the weathering profile is approximately 75–100 ft. below.

(*b*) *Weathering profiles and soils in the Sudan*

(i) *Background.* The area of two granite batholiths has been studied near Qala en Nahl (13° 37′ N., 34° 57′ E.) in the Sudan. Here isolated granite hills jut out of the clay plain in a savannah landscape. Annual rainfall averages between 24 and 28 in. falling as thunder showers from May to October with over 50 per cent. of this in July and August. The mean annual temperature is 83° F. with a low humidity. Most of the plains are covered with Acacia-tall grass forest.

The area between the River Rahad and the Rahad-Atbara watershed is almost a perfect pediplain with a gentle rise of 200 m. in 100 km. The profile of this plain, normal to the River Rahad, is in most places a gently concave curve and all prominent hills occur about half-way between the river and the watershed. The granite hill masses attain heights of up to 200 m. above the surrounding plain and are invariably surrounded by sandy fringing pediments.

(ii) *Weathering profiles.* The weathered mantle is much thinner than that recorded in Hong Kong, usually less than 30 ft., but four comparable zones can be recognized. In the thinner profiles corestones are uncommon in Zone II while Zone III is composed of gravel-sized chips of iron-stained granite rock.[1] Occasionally pockets of residual debris occur over 100 ft. thick. These appear to be very similar to some of the thick profiles in Hong Kong (Ruxton and Berry, 1957, fig. 6 *e*). Zone I is a reddish-brown clayey sand up to 40 ft. thick and Zone II is a very pale orange kaolinitic sand with the texture of the parent granite preserved and may be up to 50 ft. in thickness.

(iii) *Lateral variations.* The sequence hill, pediment, and plain corresponds roughly with a surface cover of rock or boulders, sand, and clay (Fig. 5) and there are usually angular junctions of slope between each.

The hills are mantled with a thin patchy cover, seldom more than 12 ft. thick, of low zonal material (III and IV). Occasionally a thin veneer of dark brown clayey soil occurs in depressions overlying some Zone II debris. After the rainy season water is retained in rock fissures and weather pits and this sustains a large number of broad-leaved deciduous trees. Some weather pits retain water all the year round and are fed by the rock fissures (usually along sheet joints).

The fringing pediments separating the hills from the plains have a concave surface profile and slope angles of 1–10°. A reddish or grey-brown arkosic silty sand up to 6 ft. thick forms an upper migratory layer over the sedentary weathering profile. On the lower pediment this is often veneered with patches of dark grey clayey silt. The underlying profile is usually from 6 to 30 ft. thick and is well differentiated into zones.

[1] It is useful to separate two types of Zone III debris. Zone III*a* is composed of dominant compound fragments of rock, while Zone III*b* contains dominant corestones. Zone III*a* is more common in the Sudan, while Zone III*b* predominates in Hong Kong.

At Jebel Qasim Zone I is a reddish-brown quartzose sand or gravel with no textures of the parent granite preserved. It is often very poor in feldspar and in clay. Zone II is a pale brown arkosic sand or gravel with some relicts of the granite texture preserved in places. It has a moderate content of feldspar and clay. Zone III debris is composed chiefly of gravel-sized chips of fragmented and iron-stained rock and is rich in feldspar with a moderate clay content (Ruxton, 1958*a*).

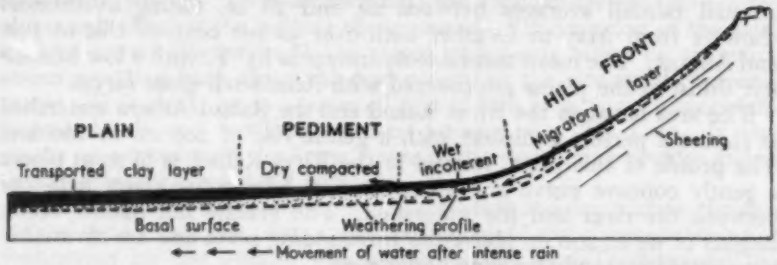


FIG. 5. Representative section near Qala en Nahl showing the form of the weathering profile and migrating debris on the concave slopes of hill, pediment, and plain.

On the upper part of the pediment around most of the hills a ring of moist incoherent debris retains some water within the weathering profile. This rests on the basal surface,[1] and persists throughout the year. On the lower pediment the dry compacted debris is much less permeable and retains little water in the dry season. The whole pediment surface supports a thin grass cover but broad-leaved deciduous trees are practically confined to the upper pediment.

The plain has a thick cover (from 3 to 20 ft.) of dark grey silty clay with kankar nodules and a deeply cracked surface in the dry season. It is almost a flat surface with gradients rarely more than 1 in 100 and is practically impermeable. Below the clay is usually a thin truncated weathering profile resting on solid rock at shallow depth, though in places thick pockets of residual debris occur.

(iv) *Erosion.* Erosion is proceeding most rapidly on the retreating concave hillslopes which are covered with some weathering debris and the material removed is being transported by creep and sheetwash across the pediment. During transport across the pediment the feldspars are decomposed to clay and much of the quartz is disintegrated to a fine sand.

Sub-surface erosion is intense beneath the upper pediment and 60–70 per cent. of the original rock may be removed by solution and mechanical eluviation (Ruxton, 1958*a*). This material is washed out on to the surface along a seepage line which separates the upper from the lower pediment. Thus the pediment is the site of large-scale rock reduction, both physical and chemical, and the fine material is washed off on to the clay plain.

The lower pediment with its covering of compacted debris is degraded

[1] The *basal surface* is the upper limit of continuously solid rock, see Ruxton and Berry, 1958.

by a slow sheetwash or by gullying. The lateral erosion by gullies truncates the weathering profile and the outer margins of the pediments become part of the plain, being in turn mantled by an alluvial clay cover.

The drainage density on the clay plain is extremely low and many hills have no stream courses within two miles of them. Under these circumstances the clay cover is very stable and is only slightly affected by sheet and rill wash during intense storms. It is here that the mature soil profiles on the clay are completely separated from the coarse-textured, truncated weathering profiles, though all the debris has been derived from one parent rock.

III. *Subsurface Water*

Three distinct water bodies may occur in any one locality: a soil water body; a weathering profile water body; and a rock water body (Fig. 1).

(i) *Soil water.* During and after heavy rain, water percolating down through the soil is held up on the illuviated B horizon or at a hardpan layer. This leads to surface slips and slumps of soil as the water soaks laterally along this layer (Ruxton and Berry, 1957, pl. I, fig. 1). Some water travels on down into Zone I debris where it is held up again. On hills with convex slopes in Hong Kong this causes seepage and eluviation in the lower Zone I debris at the valley side (ibid., fig. 15). Later catastrophic gullying occurs.

It is unlikely that vertical percolation will penetrate right through non-eluviated Zone I debris. Deepest penetration is expected down root channels but these do not normally extend more than 30 ft. below the surface. In Hong Kong a section was examined on a convex hill after more than 15 in. of rain had fallen in two days. Whereas Zone II was quite dry and powdery, the upper part of Zone I and the lower soil horizon remained very wet and sticky for many days.

(ii) *Weathering profile water.* On the upper part of a concave slope where a thin patchy soil is developed on low zonal debris, considerable percolation occurs after heavy rain. A lateral movement of water then takes place through the weathering profile above the basal surface sometimes emerging as a valley-side spring. During and after intense storms flow may be sufficient to move any clay present through the interstices of the larger grains. This clay may then seal up the fissures in the bedrock, or it may be swept laterally towards the valley choking up the weathered debris near the stream.

Fluctuations in this water body will occur seasonally and levels may vary between the basal surface and Zone I. It can of course merge with the soil water body. At the base of a concave slope conditions may arise where this water is actually under a head and it may be forced into the Zone I debris and the lower soil, perhaps carrying with it particles of clay.

(iii) *Rock reservoirs.* Many references to water supply in granite rock terrains indicate the importance of joints and fissures as small water reservoirs (Dixey, 1950, pp. 226–33). These are usually irregular and

discontinuous water bodies which may fluctuate vertically with the seasons and laterally with the chance connexions of joints.

IV. *Discussion*

Under varied relief on granite rocks, weathering profiles have formed slowly to an extent determined by time, climate, structure, erosion, and topography. Active migration of the weathered material takes place depending on mobility (the ease of removal) and slope. During migration the weathered material becomes further comminuted and intermittent weathering of it continues. The thickness of the regolith at any one time is thus a function of the rate of lowering of the basal surface and the rate of erosion and migration. At some stage in the weathering development, either *in situ* or during migration, a continuous vegetation cover gains hold and soil is formed. If the migratory or transported material is stabilized for a sufficient period it may be differentiated into distinctive layers parallel with the ground surface forming a soil profile.

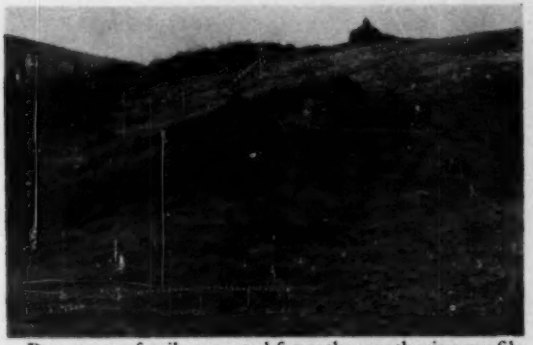
Surface removal of soil and sub-surface renewal of the residual debris by a lowering of the basal surface is an important type of erosion and it necessitates a layer of migrating material. But any particular area covered with a layer of migrating material will only be lowered by this process when downslope migration from it exceeds the material supplied to it from above. Here lowering is usually effected by the incision and lateral cutting of water courses. Weathering debris formation and removal are most active on retreating concave faceted hillslopes. On footslopes, valley-side strips, pediments, and plains, active soil profile formation occurs above complete or truncated weathering profiles.

In one geomorphic cycle there will be a complex sequence of weathering, soil formation, and migration of material. Within this cycle many variations in the relationships between weathering profiles and the overlying soils can occur. The relationships described above occur most commonly as a result of a degree of uniformity in the processes involved.

As indicated above, the weathering profile extends laterally on slope retreat and vertically on rejuvenation. Soil profile formation begins and extends vertically from the ground surface under a cover of vegetation, usually well above the fresh solid bedrock. The nearest approach to soil development direct from bedrock is in some weathering pits (Smith, 1941).

Soils develop more rapidly than complete weathering profiles and a thick weathering profile can be truncated several times and each time a soil cover develops unconformably upon it. Changes of climate or other factors might also result in several episodes of soil formation and removal on one mass of Zone I debris.

Whereas the weathering profile is adjusted to the structure and the susceptibility to weathering of the bedrock, soils rarely reflect features of bedrock structure and may mask its character. If the proposed distinction between the two profiles is adopted the term soil erosion on a granitic area would relate to the loss of that invaluable surface layer. Weathering debris erosion follows soil erosion and in Hong Kong is the main cause



a. Remnants of soil separated from the weathering profile by a stone pavement on a convex hill on granite in Hong Kong

b. Zones I, on the top, II*a*, in the middle and deeply dissected, and II*b*, covered with slopewash and vegetation, on a convex hill on granite in Hong Kong. The thickness of this section is about 100 ft.

c. A grass cover with immature soil on Zones I and II on a convex hilltop on a weathered rhyolitic ignimbrite (welded tuff) in Hong Kong. The height of the section is about 20 ft. on the right-hand side of the photograph

L. BERRY *and* B. P. RUXTON—PLATE I

of stream overloading, flooding, dam silting, and harbour filling which results.

Even in areas where soil and vegetation have been entirely removed by erosion and bare porous Zone II forms the ground surface some utilization is possible. The debris is readily terraced and heavy watering and manuring allows a small crop of vegetables to be grown. This is common procedure in Hong Kong where every inch of land is valuable.

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STIMULATION OF BACTERIAL PROTEOLYSIS BY ADSORBENTS

EVA F. ESTERMANN[1] AND A. D. McLAREN

(Department of Soils and Plant Nutrition, University of California, Berkeley)

Summary

A comparison of the initial rate of NH_3 production from protein adsorbed on kaolinite and non-adsorbed protein by bacteria showed that adsorption enhanced the rate. This effect occurs with both adsorbed and non-adsorbed organisms, and disappears when a non-adsorbed substrate (denatured lysozyme predigested by chymotrypsin) is used. With *Flavobacterium* sp. the effect occurred with a dilute inoculum and disappeared with a concentrated one. Shaking cultures of *Flavobacterium* sp., which ordinarily is *c.* 98 per cent. adsorbed to kaolinite, and of *Pseudomonas* sp., which is only *c.* 30 per cent. adsorbed to kaolinite statically, which might dislodge organisms from the clay, did not decrease rates of NH_3 liberation. It is concluded that the kaolinite acts as a concentrating surface for adsorbed substrate and exoenzymes, and thereby brings about a more rapid breakdown of substrate. *Flavobacterium* sp. readily attacks protein adsorbed on bentonite with a resulting decrease in (001) X-ray diffraction spacing.

Introduction

In the soil, and in many other natural habitats, reactions are carried out in a strongly adsorbing environment. The presence of large surface areas can affect the course of a reaction. A microbial hydrolysis occurring in soil, for instance, may have any or all of these complications: the organism may be adsorbed, its exoenzymes may be adsorbed, the substrates may be adsorbed, and the split products may be adsorbed.

Some aspects of enzymatic reactions in the presence of clay have already been presented (McLaren, 1954 *a*, *b*, 1956, 1958). An excellent review of literature on enzyme activity at liquid–gas, liquid–liquid, and liquid–solid interfaces has recently appeared (Fraser, 1957). However, the adsorption of enzymes and microbes in soil and the effect of adsorbents on microbial activity have not received current review. A discussion of these topics will precede some experimental observations on proteolysis of substrates adsorbed on kaolinite by pure cultures of micro-organisms.

Literature Review

Enzymes in Soil

Although free enzymes must certainly be present in soil in small amounts as the result of lysis of bacteria or of exoenzyme production, little is known about their activity or durability in this adsorbing medium. A brief survey is given by Haig (1955). Experimental demonstration of enzyme activity in a medium sterilized with respect to

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bacteria is a difficult accomplishment, for most sterilization methods mild enough not to denature proteins are dubious in efficacy. Conrad's (1944) early work on urease-like activity in soil was done using toluene as an antiseptic. More or less complete transformation of urea nitrogen to ammonia nitrogen was found. In some soils, addition of toluene even increased the rate of urea decomposition. Conrad (1944) has suggested that toluene accelerates release of urease from living and dead cells, and therefore the phenomenon is not one connected with enzymes of the soil, *per se*. As Drobnik (1955) points out, after partial sterilization of soil the participation of single groups of organisms changes, i.e. some organisms are inhibited, others are unaffected, and still others are encouraged.

Toluene has been used as a sterilizing agent by other groups of workers interested in soil enzymes, notably Hofmann and Seegerer (1951–4). In such soil-toluene systems, they have demonstrated the presence of saccharase, urease, proteinase, β-glucosidase, α- and β-galactosidase, and have demonstrated pH optima and heat sensitivity for these enzymatic reactions. The authors feel that the surprisingly high enzymatic activity they were able to show is traceable to enrichment by the retentive and preservative capacity of the soil, through adsorption, for the enzymes released into it by death and autolysis of micro-organisms. The aim of this group is to develop a test of the biological activity of soil through enzymatic measurements which can be correlated with soil fertility. Drobnik and Seifert (1955), using saccharase and amylase activity of soil as an index, have not been able to demonstrate a simple relationship between fertility and enzyme activity. Balicka and Trzebinski (1956) report a correlation between viable count of micro-organisms and enzyme activity of soil.

Haig (1955) has investigated urease and esterase activity in soil using both toluene and ethylene-oxide sterilization. Application of the former treatment revealed urease activity while the latter did not. However, ethylene-oxide treatment may inhibit the enzymes. McLaren *et al.* (1957), avoiding the ambiguity of heat or chemical soil sterilization, have utilized electron-beam cold sterilization in a demonstration of urease-like activity in a Dublin soil from California. This same soil showed no trypsin-like activity. Pepsin and cathepsin-like activity, but not trypsin activity, were found in a few Italian soils surveyed by Antoniani *et al.* (1954) using a different approach—that of extracting an enzyme fraction from soil using biochemical techniques of extraction and precipitation. These investigators have made the interesting observation that CO_2 production of some of these soils increased after cold storage, and speculated that this treatment may increase soil enzymatic activity. Incidentally, work in plant pathology indicates that viruses may remain in the soil for several years adsorbed to the clay and protected against destruction (Thung, 1955; Van der Want, 1951).

The increasing application of biochemical techniques to the demonstration of the presence and properties of enzymes in soil will doubtless yield much information in the future. Although the source of all the enzyme activity in soil is ultimately microbial, techniques must be

sharpened to distinguish extracellular enzyme activity in soil from residual microbial activity due to incomplete sterilization, and from intracellular enzymes of dead cells.

Adsorption of Bacteria in Soil

In discussing the proteolytic bacteria and enzymes of soil, consideration should be given to the relationship between soil bacteria and their environment. Although current literature is not much concerned with bacterial adsorption, much information on this subject has been obtained in the past, particularly by German and Russian workers. Actually, most workers in the field prefer the term 'adhesion' to 'adsorption', as the mechanisms have not been well delineated (Dikusar, 1940; Gunnison and Marshall, 1937). In this discussion we shall for convenience retain the term adsorbent, but the process will be called adhesion. The factors affecting adhesion of bacteria to colloids may be divided for discussion into those characteristic of the organism involved, those characteristic of the adsorbent, and those involving the experimental techniques.

The type of adsorbent is an important factor. Various soils differ in their adhesive capacities (Minenkow, 1929; Peele, 1936; Waksman and Vartiovaara, 1938) for bacteria, and in some cases the differences can be correlated with mechanical analyses (Dianowa and Woroshilowa, 1925; Novogrudsky, 1936). Those soils or muds containing higher silt and clay percentages are efficient adsorbents for bacteria. Soil has been found to vary in adsorptive capacity for bacteria with seasonal changes (Novogrudsky, 1936) and with changes in aggregate physical properties (Chudiakow, 1926). Oxidation or autoclaving did not affect the adhesive capacity for bacteria of sea-bottom sediments, but leaching with 10 per cent. HCl did (Rubentschik *et al.*, 1936). This may be due to removal of aluminium by the leaching.

Other adsorbents for bacteria which have been studied are peat (Lochhead and Thexton, 1947), gels (Gunnison and Marshall, 1937; Peele, 1936; Salus, 1917), filter paper (Friedberger, 1919), talc, quartz (Chudiakow, 1926; Tschapek and Garbovsky, 1950; Gunnison and Marshall, 1937; Oksentian, 1940), kaolin (Gunnison and Marshall, 1937; Oksentian, 1940; Salus, 1917), $BaSO_4$ and $CaCO_3$ (Gunnison and Marshall, 1937). Gunnison and Marshall (1937), comparing the adsorption of *E. coli*, *Cl. welchii*, and *L. acidophilus* on charcoal, kaolin, $CaCO_3$, and alumina, found the type of adsorbent less important than the type of organism used. Eisenberg (1918), who studied about fifty adsorbents, found some correlation of adsorption efficiency with the amount of surface presented by various types rather than with their intrinsic natures. Peele (1936) found similar adhesion percentages with silt loam and $Al(OH)_3$ gel, but found no adhesion to $Fe(OH)_3$ gel. Salus (1917), however, was able to adhere *E. coli*, *B. typhus*, and *B. faecal. alkaligenes* to the latter. Both he and Oksentian (1940) believe the amount of electrokinetic potential of the adsorbent to influence adhesion; the less negative adsorbents being more efficient in removing negatively charged bacteria from suspension.

The size fraction of the adsorbent has been shown to be of importance

with quartz by Chudiakow (1926). Using *E. coli*, *B. mycoides*, *B. prodigiosum*, and *B. mesentericus*, he found maximum adhesion in the range of 0·003 to 0·03 mm. particle diameter. Chudiakow also notes that when the size of the adsorbent is reduced and approaches that of the bacteria no adhesion takes place.

Dianowa and Woroshilowa (1925) found that increasing the amount of soil as adsorbent in the system increased adhesion of soil organisms up to a point. Tschapek and Garbovsky's (1950) careful work with *Azotobacter* adsorbed on quartz also shows this. Gunnison and Marshall (1937) did not find such an effect with kaolin as an adsorbent for intestinal flora, but may have been working only in the range of constancy.

When the adsorbent has exchangeable bases, as is the case with soil and clays, the cation on the exchange complex affects adhesion. Peele (1936) with *Azotobacter* adsorbed on soil, and Tschapek and Garbovsky (1950) with *Azotobacter* adsorbed on quartz, found that adsorption is higher with increasing salt concentration. When excess ions were leached out, Na^+, Li^+, NH_4^+, and K^+-saturated soils showed more release of adsorbed bacteria, and Al^{+++}, Fe^{+++}, and Mn^{++} less. However, toxicity considerations may enter into these observations. Contrariwise, Fe^{+++} and Al^{+++}-saturated soils adsorbed far more *Azotobacter* than Na^+, Li^+, NH_4^+ or K^+-saturated soils.

In general, investigators have found the type of organism a more important factor in determining adhesive ability than the type of adsorbent. The organisms most studied have been *Azotobacter* (Peele, 1936; Tschapek and Garbovsky, 1950), *B. mycoides* (Minenkow, 1929; Novogrudsky, 1936; Peele, 1936), and *E. coli* (Chudiakow, 1926; Dikusar, 1940; Gunnison and Marshall, 1937; Novogrudsky, 1936; Salus, 1917). Some authors have observed that gram-positive organisms are taken out of suspension to a greater extent than gram-negative ones (Novogrudsky, 1936), and Eisenberg (1918) reports a relative enrichment of gram-negative organisms in a mixture because of selective adsorption of gram-positive ones. Gunnison and Marshall (1937), however, did not confirm such selective adsorption in their studies. Others have presented evidence that actively motile organisms are more weakly adsorbed (Chudiakow, 1926; Dikusar, 1940; Karpinskaya, 1926). Possibly these two observations are related; many common gram-negative soil organisms are polarly flagellated and more actively motile (*Pseudomonas*). Zooglea are weakly adsorbed by quartz sand (Chudiakow, 1926). One can experimentally replace one adsorbed species with another more readily adsorbed (Chudiakow, 1926; Eisenberg, 1918; Rubentschik *et al.*, 1936) and can also separate organisms and spores by selective adsorption (Friedberger, 1919; Novogrudsky, 1936). For example, *Serratia marcescens* was capable of desorbing an unknown gram-negative organism from salt lake sediments, and itself became adsorbed (Rubentschik *et al.*, 1936).

A fixed quantity of adsorbent may become saturated with bacteria and be unable to accept any more. Dianowa and Woroshilowa (1925) and also Rubentschik *et al.* (1936) found that the higher the number of bacteria inoculated into soil, the higher is the absolute number of

adsorbed bacteria; however, the percentage of organisms adhering decreases. The latter, however, observed a zone of maximum adsorption with *Serratia marcescens*. Tschapek and Garbovsky (1950) showed that with 2 g. of quartz the numbers of *Azotobacter* adhering increased with numbers of organisms added until 40 million; further increase did not increase the number adhering.

The remaining factors to be discussed are concerned with the environmental conditions which affect adsorption. Investigators generally have combined adsorbents and bacteria for a fixed length of time, with agitation, then separated the adsorbent either by simple sedimentation (Peele, 1936), centrifugation (Gunnison and Marshall, 1937; Tschapek and Garbovsky, 1950), or filtration (Eisenberg, 1918). Both Gunnison and Marshall (1937) and Tschapek and Garbovsky (1950) observe that adhesion takes place very quickly. The former found no difference in adhesion of bacteria to kaolinite in 15 minutes and 3 hours. Violence of agitation did not affect adhesion. The latter found increasing adhesion of *Azotobacter* to quartz up to 10 minutes, and very little increase thereafter to 1 hour.

The pH at which adhesion takes place has been shown to be markedly influential. Gunnison and Marshall (1937) found the degree of adhesion of five organisms to be greater at pH 5·6 than at 7·2. *L. acidophilus* was the only exception. Peele (1936) worked over a pH range of 6·3 to 7·6 and found both for *Azotobacter* and *B. mycoides* on soil that adhesion dropped slowly from pH 6·3 to 7·3, and then rapidly from 7·3 to 7·6. Tschapek and Garbovsky (1950) also found a sharp pH differentiation for adhesion of *Azotobacter* to quartz, but their maximum was at pH 4·5 and dropped steadily to pH 5·5, after which there was gradually less adhesion. At pH 7·2 no more adhesion took place. Novogrudsky (1936), with *E. coli* and *B. mycoides* adsorbed on soil, found a minimum at pH 5·8 for *E. coli* and at 6·7 for *B. mycoides* and then a rise again at higher pH values.

Adhesion of bacteria to colloidal particles has been difficult to demonstrate microscopically. Chudiakow (1926) has published some pictures, as have Peele (1936) and Beutelspacher (1955). However, drying of the sample, staining, convection currents in hanging drops, all make this phase of study a most ambiguous one because of the possibility of artifacts. Kalyuzhny (1957) has recently reported a streaming chamber in which adsorption of yeasts to cellulose fibres can be observed directly.

The phenomenon of adhesion of bacteria to solids must certainly be taken into account in interpreting soil plate counts, water purification, &c. Only non-adhering species may be observed on plates, or several bacteria adhering to a particle may grow into a single colony. Selective adsorption may be the cause of a false picture of the composition of a mixed population (Chudiakow, 1926). In water purification, the fact that adhesion is rarely 100 per cent. efficient must be considered (Rubentschik *et al.*, 1936).

Bacterial cells can also act as adsorbents for enzymes. Muggleton and Webb (1952) have shown that proteolytic enzymes from soil actinomycetes adsorb on heat-killed cells of *B. lactis aerogenes* and lyse them.

Lysozyme also lyses some bacteria by removing the cell walls, e.g. from *B. megaterium* (Weibull, 1953). McCalla (1941) has made the suggestion that bacteria may get their nutrients from materials adsorbed on themselves and extends this view to postulate that the toxicity of hydrogen ion is due to its being difficultly replaceable by Ca^{++} and other ions needed by the organisms.

The adhesion of bacteria to solids has not been observed to interfere with viability (Oksentian, 1940). Waksman and Vartiovaara (1938) and Zobell (1943, 1946) both remark that adhesion, if it brings bacteria into contact with a nutrient supply, may soon be followed by a rapid increase in bacterial numbers. Conn and Conn (1940) also find that addition of colloid stimulates bacterial multiplication. Both Rubentschik *et al.* (1936) and Lochhead and Thexton (1947) find that adsorbed bacteria in soil survive storage without significant changes and that such 'adhesion storage' is an effective means for preserving cultures. Synthetic media consisting of about 95 per cent. sand and 5 per cent. bentonite have been devised in which pure cultures of bacteria may be studied (Conn and Conn, 1941; Mahdok, 1937). Unfortunately the use of such media for studying pure cultures at solid–liquid interfaces has not been pursued.

Effects of Adsorbents on Bacterial Activities

Depressing effect. Conflicting reports exist in the literature regarding the effect of added adsorbents on bacterial physiological activities. Chudiakow (1926), using soil added to cultures of *B. mycoides*, *B. prodigiosum*, *B. megaterium*, and *B. coli commune*, found severe decrease in CO_2 evolution from nutrient media. Similarly, addition of soil to *Azotobacter chroococcum* was found by Peele (1936) to depress CO_2 evolution, in proportion to the abilities of the soil preparations tested to adsorb bacteria. Dianowa and Woroshilowa (1925) also connect a lessened biological activity in soil with the degree of specific adsorbability of a bacterial species and the degree of adsorbing strength of the colloid. An active controversy regarding the need for adsorption of ammonium ion in nitrification is of current interest (Goldberg and Gainey, 1955; Lees and Quastel, 1946). The conditions chosen for nitrification by the two groups, however, are by no means comparable.

Ensminger and Gieseking (1942) showed that adsorption of protein in the layer lattices of clay minerals protected it from proteolysis by enzymes and microbes. The adsorption of albumin and hemoglobin by base exchange clays was found to interfere with the enzymatic hydrolysis of these proteins in both acid pepsin suspensions and alkaline pancreatin suspensions. Kaolinite, a clay mineral with a very low base exchange capacity, had no significant effect on the hydrolysis of albumin and hemoglobin. The authors presented two possible explanations for the protection effect: (1) that partial adsorption of the enzymes on the clay rendered them inactive, and (2) that adsorption oriented protein molecules in such a way that the active groups were inaccessible to the enzymes. In this work and most of those mentioned below, adsorbents have been compared by weight, rather than total surface area.

Allison, *et al.* (1949) demonstrated that addition of montmorillonite

to sand cultures caused a reduction in loss of added carbon. The study was extended (Pinck and Allison, 1951; Pinck *et al.*, 1954) to the decomposition of gelatin-bentonite complexes and mixtures by soil infusions. Gelatin and egg-albumin complexes, prepared by several methods and vacuum-dried, showed a resistance to proteolysis varying with the protein-clay ratio. Up to about 20 per cent protein (equivalent to a monolayer between the clay sheets), decomposition was limited to about 20 per cent., corresponding to that material likely to be adsorbed on the exterior surface of the clay. The authors suggest that interlayer spacings are not increased enough to permit entrance of enzymes. When 30–50 per cent. protein was incorporated into the complexes, decomposition proceeded at about the same rate as if no clay were present. Mixtures of protein and clay at low protein levels also showed a lessened protective action. X-ray diffraction data on the gelatin-montmorillonite systems showed that in the high protein-clay complexes, decomposition by mixed soil organisms resulted in decreasing 001 spacings until approximately a 'monolayer' of protein remained. Estermann *et al.* (1959) found that some pure cultures of bacteria acting on a monolayer of lysozyme adsorbed on bentonite could reduce the 001 spacing to 15 per cent. of the value for a monolayer and liberate 63–75 per cent. of the available nitrogen as NH_3.

Birch and Friend (1956) have confirmed the protective action of gelatin on bentonite, and found that kaolinite did not have a similar effect. They observed that repeated wetting and drying of the complexes succeeded in partly releasing the bound protein.

McLaren and Estermann (1956), however, have shown that monolayers of denatured protein adsorbed on kaolinite can be attacked by chymotrypsin at about the same rate as can non-adsorbed protein. Estermann *et al.* (1959) also demonstrated that protein monolayers on bentonite are susceptible to rapid attack by chymotrypsin, a bacterial proteinase from *B. subtilis*, and by pure and mixed cultures of soil microorganisms. Dried, rewetted protein-montmorillonite complexes were considerably more resistant than merely adsorbed proteins. The 'protective' action of expanding layer lattice clays seems to be due to factors other than simple adsorption of substrates or inactivation of enzymes or bacteria by adsorption.

Phosphatases as well as proteinases have been reported to be inhibited by the presence of clay minerals in the system (Goring and Bartholomew, 1950; Mortland and Gieseking, 1952). Though no specific clay-substrate compounds were made, the addition of colloid inhibited to some extent the hydrolysis of glycerophosphate, phytin, fructose diphosphate, and lecithin. In all cases, Wyoming bentonite (montmorillonite) was the most effective, and kaolinite the least (although still showing an effect), with several soil colloids falling between. The inhibitory action varied with the substrate. An experiment utilizing membrane separation of the enzyme from the clay-plus-substrate system showed that the inhibition was partially due to apparent inactivation of the enzyme by the clay and not an effect on the substrate. Adsorption studies were not made in connexion with these observations.

Lynch and Cotnoir (1956, 1957) have studied the degradation of various soluble and insoluble carbohydrate materials, crop residues, and proteinaceous materials in the presence and absence of clay minerals, both with soil micro-organisms and enzymes. The general protective effect of clay, especially montmorillonite, was found in many cases, although with some of the complex natural materials used the results cannot be evaluated in terms of mechanisms. In some cases, such as corn polysaccharides, pectin, and yeast extract, little protection by montmorillonite was observed. Some protection was observed with insoluble materials such as cellulose dextrins and oat-straw residues, which was interpreted as probably being due to adsorption of intermediate breakdown products or of the enzymes involved. Using pure enzymes, cellulase and hemicellulase activity was found to be reduced by montmorillonitic clays, whereas amylase activity underwent no reduction. Again in these studies actual determinations of adsorption were not made. Attapulgite did not interfere with gelatin decomposition (CO_2 evolution) in soil cultures, while 33 per cent. protection of cellulose dextrin was observed in the presence of attapulgite. Attapulgite did not inhibit pure enzyme activity.

Stimulating effect. On the other hand, a great many observations of the stimulating effect of colloids on bacterial activity have also been made. Sohngen (1913) observed a stimulating effect on nitrogen fixation by *Azotobacter*, hydrolysis of starch by *B. ochraceus*, bacterial urea decomposition, alcohol oxidation, and petroleum oxidation by charcoal and silica. Stimulation by soil colloids of nitrogen fixation by *Azotobacter* was also reported by McCalla (1939). Plevako and Kinsburskaya (1932) observed a stimulating effect of charcoal in yeast alcoholic fermentation. Kalyuzhny (1957) found that adsorption of yeasts to cellulose fibres stimulated their multiplication and fermentation. Turner (1955) has found that addition of charcoal to the rooting medium of clover plants inoculated with rhizobia stimulated nodulation and traced the effect to removal of inhibitory compounds secreted by the root. Similarly Skinner (1956) has found that clays added to mixed fungal cultures inhibited antibiotic activity of one organism towards another. Pollock (1947) with *H. pertussis*, and Gorelick *et al.* (1951) with *Brucella* have found that charcoal in bacterial media removed toxic substances and permitted growth.

Stimulating effects of colloids on microbial growth have been correlated with nutrient concentration. Heulelekian and Heller (1940) and Zobell (1943) have both shown that increase in surface stimulated increased growth when nutrient supply was limited. Zobell (1943, 1946) remarks that adsorption of nutrients on solid surfaces provides a concentrated region where subsequent adhesion of bacteria provides an entrapment for enzymes secreted by the organisms and nutrient hydrolysates released to the organisms. Without the concentrating effect of the surface, enzymes released by the organisms would be dissipated and diluted, and nutrient hydrolysates would not reach the organism efficiently. Vogler and Umbreit (1941) have found that *Thiobacillus thiooxidans* must remain in contact with its insoluble substrate sulphur

and that shaking or separating the bacteria from the sulphur particles with collodion sacs sharply diminished oxidation. Dikusar (1940), in his extensive review of the Russian literature, concludes that the suppressing effect of adsorption on bacterial functions has not been proved, because various factors making up the effect had not been controlled. He lists as suppressing factors the toxicity of the soil solution and weak aeration, and as favouring factors the setting up at the interface of favourable conditions related to the exchange of substances; that is, gases, enzymes, nutrients, split products.

In summary, the physical relationships between enzymes, bacteria, and colloids may affect physiological activities in soil and other environments in a variety of ways. Bacteria, enzymes, substrates, and products can be adsorbed. Such adsorption may depress activities by removing enzymes and substrates from contact or by fixing them in inaccessible positions on the colloid. On the other hand, colloids may improve aeration, remove toxic substances, or act as concentrating centres in dilute media, thus enhancing physiological activity.

In the following section we report some observations on the effect of kaolinite and bentonite suspensions on the proteolytic behaviour of the soil organisms *Flavobacterium* sp. and *Pseudomonas* sp., as measured by NH_3 production from a mineral-salt solution plus protein. The effects of the size of the microbial inoculum, the adsorption of bacteria, and the adsorption of substrate are evaluated.

Experimental

Materials and Methods

Denatured lysozyme-kaolinite complex (KHLC)

Details of most of the experimental materials and procedures are given elsewhere (Estermann *et al.*, 1959; McLaren and Estermann, 1956). Briefly, a monolayer of sterile heat-inactivated lysozyme (Armour Laboratories) in water was adsorbed on sterile potassium kaolinite in suspension in dilute phosphate buffer of pH 4. Washed cell suspensions of the micro-organisms tested, in mineral-salt solution, pH 7·6, were added to the denatured lysozyme-kaolinite complex (KHLC) and incubated in 92-ml. capacity screw-capped tubes. Tubes were incubated on their sides at room temperature stationary or, where indicated, on a Brunswick rotary shaker at 300 r.p.m. The contents of the tube (2 ml. total) were spread out as a thin sheet, to allow maximum aeration. The denatured protein supplied the only carbon and nitrogen source for the organisms; as a consequence, NH_3 was formed and usually raised the pH to 8·0. At intervals tubes were opened, 0·5 ml. 0·05 N H_2SO_4 was quickly added to kill the organisms and retain NH_3, and total NH_3 was determined by Conway diffusion followed by Nesslerization (Conway and Byrne, 1933). Other sets of tubes were prepared similarly using lysozyme split products in place of denatured lysozyme. To obtain lysozyme split products, a solution of heat-denatured lysozyme, 2 mg. per ml., was digested for 24 hours by 0·0118 mg. chymotrypsin in 5 ml. 0·1 M K_2HPO_4, pH 8·5. After digestion, the solution was autoclaved to stop

enzyme action. Only 13 per cent. of such split products are adsorbed on kaolinite in 2/3 Universal Buffer (McLaren and Estermann, 1956). Sets of tubes without kaolinite were prepared and inoculated in a similar manner. Each tube contained a total of 1 mg. lysozyme or lysozyme split products.

Denatured lysozyme-bentonite complex (BHLC)

The preparation of a monolayer of denatured lysozyme on Wyoming bentonite (1 mg. lysozyme per 0·78 mg. bentonite) has been described elsewhere (McLaren *et al.*, 1958; Estermann *et al.*, 1959). Screw-capped tubes of BHLC were inoculated, incubated, and analysed as described above for KHLC. The total clay-surface area in BHLC and KHLC experiments was equal.

Organisms

A *Pseudomonas* sp., isolated from Dublin soil from California, has been described elsewhere (McLaren and Estermann, 1956). In addition a gram-negative rod tentatively identified as *Flavobacterium* sp. was also isolated from Dublin soil by enrichment culture in denatured lysozyme-kaolinite (KHLC) mineral-salt suspension, followed by plating the most numerous organisms on potato-dextrose-peptone agar. *Flavobacterium* sp. is a gram-negative rod, $0{\cdot}5 \times 1{\cdot}5\ \mu$, having no endospores. Attempts to demonstrate flagella with stains and electron microscope were unsuccessful. Colonies on agar were small to punctiform, circular, convex, and entire, of a bright orange colour. The organism is a facultative aerobe, with optimum growth at 25°. The colour of the medium after growth is not changed. Gelatin liquefaction is infundibuliform and extremely rapid, and litmus milk is rapidly peptonized and slightly acid. Slight acid, but no gas, is produced from glucose and sucrose, but none from lactose. The organism hydrolyses starch and produces indole, but does not produce H_2S and does not reduce nitrates. A pleasant floral odour develops when cultures grown on pure protein plus mineral salts are treated with 10 per cent. NaOH.

B. subtilis Moran was obtained from the culture collection of the Bacteriology Department, University of California.

Adhesion of bacteria

Adhesion of bacteria to kaolinite or KHLC was determined by combining 2 ml. of a washed 24-hour bacterial culture in mineral-salt solution, pH 6·7 to pH 8·2, with 0·077 g. kaolinite or equivalent KHLC suspended in 2 ml. 0·008 M phosphate buffer, pH 3·4, in small sterile screw-capped tubes. These concentrations are the same as those used in protein-digestion experiments. The tubes were gently agitated at room temperature for 15 minutes, then centrifuged for 4 minutes in a clinical centrifuge at half speed. Tubes containing bacteria plus 0·008 M phosphate buffer, without clay, were treated simultaneously. In this way both adhesion tubes and control tubes had identical centrifugation. After centrifugation, samples of supernatant were pipetted off, suitably diluted, and used for plate counts on nutrient agar. Plates were counted

on the third and fifth days, and averages of four replications recorded. There was very little difference between third- and fifth-day counts.

Results and Discussion

Stimulation of NH_3 production from protein by bacteria

Stimulation of bacterial activities in the presence of colloidal material has been noted before (Estermann *et al.*, 1959). Such a stimulation can be seen in the left sections of Figs. 1 and 2 for the organisms *Pseudomonas* sp. and *Flavobacterium* sp. Where the substrate, denatured lysozyme, is in the adsorbed form as KHLC, the initial rate of NH_3 production is faster than when no kaolinite is present in the culture medium. This initial stimulation has also been observed with bentonite as an adsorbent and with the organisms *B. mycoides* and *B. subtilis* (Estermann *et al.*, 1959).

In order to analyse the experimental situation more closely it is necessary to vary separately the several possible adsorbing effects of the kaolinite, i.e. for bacterial enzymes, substrates, and the bacteria themselves. It has been shown that both *Pseudomonas* sp. and *Flavobacterium* sp. produce extracellular proteolytic enzymes, and adsorption of such enzymes on KHLC does not prevent proteolysis (McLaren, 1954*b*; McLaren and Estermann, 1956).

Adsorption of substrate

When kaolinite is present, but the substrate is not adsorbed (McLaren and Estermann, 1956), the stimulating effect on NH_3 production disappears. This is shown in Fig. 3, where NH_3 production by *Pseudomonas* sp. from non-adsorbed lysozyme split products is shown. The presence of kaolinite in the medium does not affect the rate of NH_3 evolution. Evidently the state of adsorption of the substrate is an important factor in stimulation of growth. No inhibition of bacterial enzymes by the clay surface is shown. Zobell (1943) and Heukelekian and Heller (1940) remarked that increase in surface stimulated increased bacterial growth, when the nutrient supply was limited, by concentrating available nutrient on the adsorbing surfaces.

Adhesion of bacteria to kaolinite and KHLC

The differences in adhesive capacity to kaolinite and KHLC among the organisms studied were marked. The results of adsorption determinations shown in Table 1 indicate that throughout the pH range used in these experiments, *Pseudomonas* sp. is less adsorbed on kaolinite or KHLC than is *Flavobacterium* sp. or *B. subtilis* Moran. Incubation of culture tubes of the former two organisms on a Brunswick rotary shaker at 300 r.p.m., which could conceivably interfere temporarily with adsorption (Vogler and Umbreit, 1941), does not influence the normal course of proteolysis of lysozyme. The results were similar to those shown in the right half of Figs. 1 and 2. It has been shown previously that an enzyme (chymotrypsin) must adsorb on an adsorbed substrate, KHLC, to cause proteolysis (McLaren and Estermann, 1956). Our

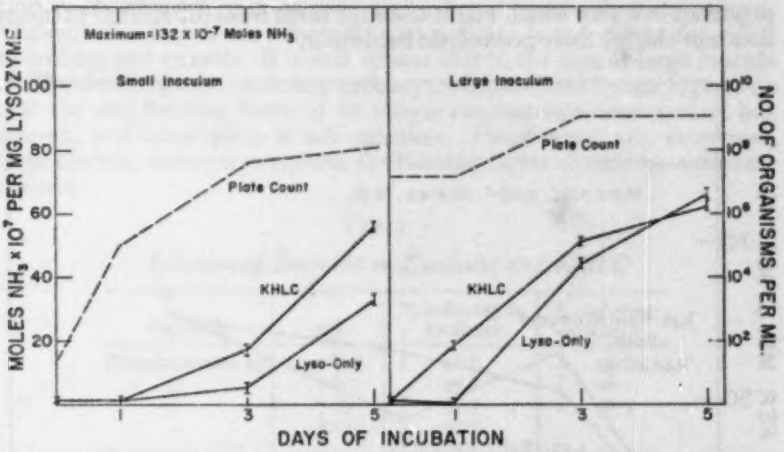

FIG. 1. Ammonia released from KHLC and non-adsorbed lysozyme in suspension by small and large inocula of *Pseudomonas* sp. in mineral-salt solution, pH 7·6–8·0. Solid lines, ammonia released (left abscissa); dotted lines, plate counts (right abscissa). Maximum possible ammonia release is 132×10^{-7} moles NH_3 per mg. lysozyme.

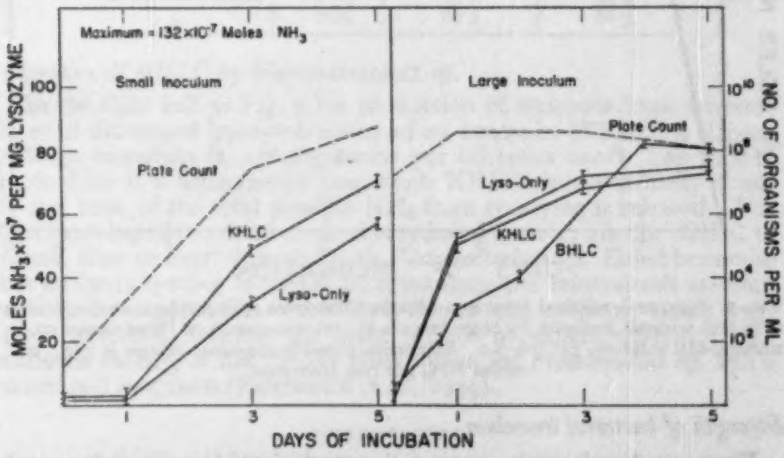

FIG. 2. Ammonia released from KHLC and non-adsorbed lysozyme in suspension by small and large inocula of *Flavobacterium* sp. in mineral-salt solution, pH 7·6–8·0 and from BHLC in another experiment by a large inoculum of *Flavobacterium* sp. Solid lines, ammonia released (left abscissa); dotted lines, plate counts (right abscissa). Maximum possible ammonia release is 132×10^{-7} moles NH_3 per mg. lysozyme.

new results indicate that only the enzyme, not the organism itself, need be adsorbed, because (*a*) the stimulating effect of kaolinite is observed both with adsorbed (*Flavobacterium* sp.) and non-adsorbed (*Pseudomonas* sp.) organisms, and (*b*) shaking cultures of the adsorbed

organism in a way which might dislodge them from the KHLC particles does not change their proteolytic behaviour.

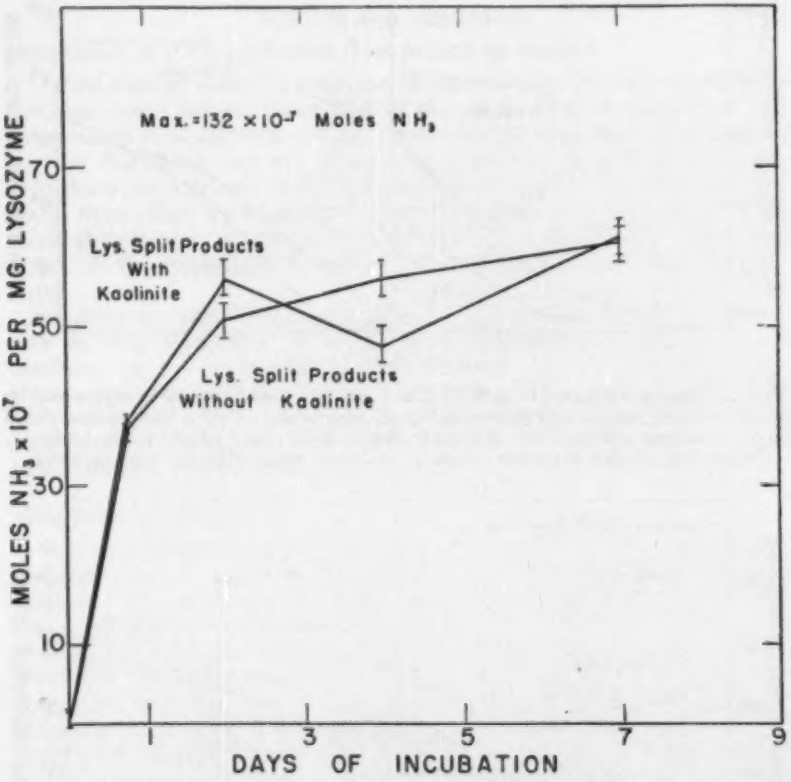

FIG. 3. Ammonia released from non-adsorbed lysozyme split products in suspension with and without kaolinite by large inocula (*c.* 10^9 organisms) of *Pseudomonas* sp. in mineral-salt solution, pH 7·6–8·0. Maximum possible ammonia release is 132×10^{-7} moles NH_3 per mg. lysozyme.

Strength of bacterial inoculum

Figs. 1 and 2 show the course of proteolysis of lysozyme alone and KHLC when dilute (*c.* 10 organisms per ml.) and concentrated (*c.* 10^7 organisms per ml.) inocula were employed. In all cases the total amount of new protoplasm produced from the 1 mg. of available protein was the same, roughly 10^9 organisms. With dilute inocula of *Flavobacterium* sp. (Fig. 2) the initial stimulation effect appeared; with concentrated inocula the effect did not appear. With *Pseudomonas* sp. the stimulation effect appears both with concentrated and dilute inocula. The effect of adsorbing the substrate on kaolinite may be to raise locally the concen-

tration of substrate and provide a site for enzyme-substrate contact. Without the clay as an adsorbent the enzyme is too dilute for rapid hydrolysis and growth. It would appear that in the case of large inocula of *Flavobacterium* sp., sufficient exoenzyme is produced by the organisms that the rate limiting factor is no longer enzyme-substrate contact but growth, and stimulation is not apparent. *Pseudomonas* sp., even with large inocula, does not overcome the limiting factor of enzyme-substrate contact.

TABLE 1

Adhesion of Bacteria to Kaolinite and KHLC

Organism	*pH*	*% adhering to kaolinite*	*% adhering to KHLC*
Flavobacterium sp.	6·8	98·6	98·8
,,	7·6	97·6	98·1
,,	7·85	98·1	96·7
,,	8·15	97·7	..
Pseudomonas sp.	6·75	48·6	8·8
,,	7·6	42·8	14·2
,,	7·85	42·3	34·4
,,	8·15	30·3	..
B. subtilis Moran	7·65	97·1	95·5
,,	7·85	83·3	62·3

Digestion of BHLC by Flavobacterium *sp.*

In the right half of Fig. 2 the production of ammonia from a monolayer of denatured lysozyme adsorbed on bentonite (BHLC) is shown. A large inoculum (*c.* 10^9 organisms per ml.) was used. The rate of proteolysis is a little slower than from KHLC, but eventually about 60 per cent. of the total possible NH_3 from lysozyme is released. The (001) spacing of the dried mineral is reduced from 47·2Å. for BHLC to 14·2Å. after 10 days' digestion with *Flavobacterium* sp. Dried bentonite has an (001) spacing of 11·1Å. as dried from the mineral-salt solution used in the experiments. *Flavobacterium* sp. can evidently attack lysozyme adsorbed between the layer lattices of expanding-lattice clay minerals readily, as has already been shown for *Pseudomonas* sp. and a mixed soil inoculum (Estermann *et al.*, 1959).

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THE DIFFUSION OF GASES THROUGH POROUS MEDIA

T. J. MARSHALL

(Division of Soils, Commonwealth Scientific and Industrial Research Organization, Adelaide, South Australia)

Summary

The effect of the obstruction of solid on the permeability of porous media is examined. From this it is concluded that, in Penman's equation for diffusion of gases through porous media, the constant 0·66 should be replaced by $\epsilon^{\frac{3}{2}}$ where ϵ is the porosity.

THE relation between permeability and the size distribution of pores in an isotropic porous medium can be given (Marshall, 1957; 1958) by

$$K = \epsilon^2 n^{-2}[r_1^2+3r_2^2+5r_3^2+\ldots+(2n-1)r_n^2]/8. \qquad (1)$$

Here K is the permeability in cm.^{2}, ϵ is the porosity in cm.^{3}/cm.^{3} of porous material, and n is the number of equal parts into which the pore space is divided—the first having the largest pores (of radius r_1 cm.), the second having the next largest (r_2), and the nth having the smallest pores (r_n). In the derivation of this equation an expression is found for an average size of necks connecting the pores. The medium is then treated as though its pore space were wholly included in a system of parallel tubes whose circular section is of that size. In order to obtain an expression for this average size, unit area of cross-section was treated as being made up of n equal parts each of uniform area ($1/n$), and porosity ϵ cm.^{2}/cm.^{2}, and each containing pores of one radius r_1, r_2,..., or r_n. For this purpose it was assumed that in isotropic material of porosity ϵ cm.^{3}/cm.^{3} the fractional pore area in any plane is ϵ cm.^{2}/cm.^{2}

In the diffusion of a gas under a partial pressure gradient, pore size is not directly important (Penman, 1940*a*). If D is the coefficient of diffusion in a porous medium and D_0 is the coefficient of free diffusion in the absence of any solid, then the ratio D/D_0 is equal to the fraction of the cross-sectional area available for free diffusion, or

$$D/D_0 = a\epsilon. \qquad (2)$$

Here, as before, the porosity, ϵ cm.^{2}/cm.^{2}, represents the fraction of the cross-sectional area that is made up of pores and a is a hypothetical fraction of ϵ representing the porosity in cm.^{2}/cm.^{2} through which gas can be considered to diffuse freely. The remainder of the porosity of the cross-sectional area thus absorbs the obstructing effects of the solid in general. The fraction a is not known, but an expression for it can be obtained by considering the viscous flow of fluids when the obstructing effects of the solid are applied to all pores. The cross-sectional area of the pores cut by a plane normal to the direction of flow will thus be considered to be reduced by the fraction a. Flow through this fraction will be unobstructed and can therefore be considered as occurring in tubes of section $a\pi r_1^2$, $a\pi r_2^2$,..., and $a\pi r_n^2$ in each of the pore-size groups

as defined for equation 1. The velocity of a fluid in cm./sec. across the plane is proportional to the sectional area of tube (taken to be circular) in each of the n groups. For the material as a whole, it is proportional to $a\pi n^{-1}(r_1^2+r_2^2+\ldots+r_n^2)$. The actual velocity, u' cm./sec., through the tubes is greater than the apparent velocity, u cm./sec., for the medium as a whole so that $u'=u/a\epsilon$. When these substitutions for tube size and velocity are made in Poiseuille's law and this is then combined with Darcy's law (Marshall, 1958), permeability is found to be given by

$$K = a^2\epsilon n^{-1}(r_1^2+r_2^2+\ldots+r_n^2)/8. \tag{3}$$

When equations (1) and (3) are compared, the free fraction of the pore space is found to be given by

$$a = \epsilon^{\frac{1}{2}}\sqrt{\left(\frac{n^{-1}[r_1^2+3r_2^2+\ldots+(2n-1)r_n^2]}{r_1^2+r_2^2+\ldots+r_n^2}\right)}. \tag{4}$$

In media with pores of uniform size, the size factor becomes equal to 1 and hence $a = \epsilon^{\frac{1}{2}}$.

Equation (4) is set up for viscous flow and the size factor appears in it because, in the derivation of equation (1), allowance is made for the reduced efficiency of a pore when the pore space with which it communicates is subdivided into a number of small pores. This effect of size can be neglected in diffusion so that equation (4) then becomes

$$a = \epsilon^{\frac{1}{2}} \tag{5}$$

as for uniform pores. Hence from equation (2),

$$D/D_0 = \epsilon^{\frac{1}{2}}. \tag{6}$$

Equation (6) is the same as the widely used equation of Penman (1940*a*) $D/D_0 = 0{\cdot}66\epsilon$, except that $\epsilon^{\frac{1}{2}}$ takes the place of 0·66. The two are compared in Fig. 1 and it will be seen that over most of the range ($\epsilon < 0{\cdot}7$) to which Penman's equation applies, the differences are not great. At any porosity between 0·36 and 0·52 they give values for D/D_0 which differ by less than one-tenth of the magnitude of D/D_0. The greatest relative differences are at the lower porosities where, in agriculture, diffusion is critical in the aeration of soil. Here the general trend of most of the data of Taylor (1949) and van Bavel (1952) is in better agreement with the curve for $D/D_0 = \epsilon^{\frac{1}{2}}$ than the straight line. Van Bavel's replicated measurements on dry materials of porosity 0·250, 0·355, and 0·415 gave mean values for D/D_0 of 0·125, 0·205, and 0·244 respectively (with low standard errors) and the corresponding values found on calculating from $\epsilon^{\frac{1}{2}}$ agree very well. They are 0·125, 0·211, and 0·267. Taylor's materials included 3-phase systems (moist materials) and in such cases the gas-filled pore space is used in the calculation instead of the total pore space. Taylor's data are more scattered and some agree fairly well with Penman's line. At high porosities between 0·6 and 0·9, the data of Penman (1940*a*, *b*) agree within one-fifth of the magnitude of D/D_0 or better (except for mica) but they are consistently below the curve. The data of Flegg (1953) include some greater deviations but at $\epsilon = 1$ equation (6) meets the requirement that $D/D_0 = 1$.

Penman used the tortuosity model of Carman (1937, 1956) as a basis for the numerical constant in his equation. It has now become evident that tortuosity and the constant in the Kozeny permeability equation (of which it forms a part) are not constants at all (Wyllie and Gregory, 1955; Marshall, 1958). If the Carman model is adopted and the resulting permeability equation is compared with equation (1), it leads to a value for

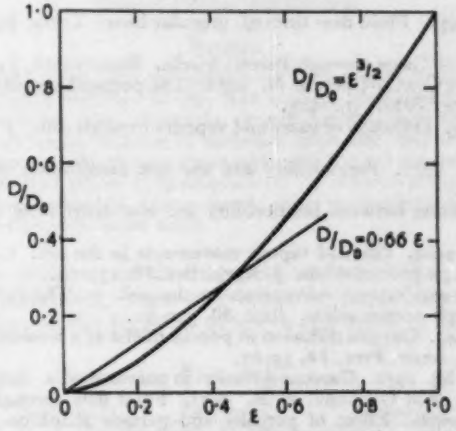

FIG. 1. Comparison of diffusion equations.

tortuosity of $\epsilon^{-\frac{1}{2}}$. This is in agreement with the present solution for a; but the concept of the lengthened tortuous path does not lend itself to the high values which are then required at low porosity.

The chance that a pore will communicate efficiently with another increases with porosity; and freedom from obstruction should apparently be represented by some function of porosity rather than by a tortuosity constant. The actual expression obtained for a depends upon equation (1), and especially upon the use of ϵ for obtaining the average neck size when one pore is fitted randomly against an opposite surface. Although there are arbitrary features in this, the equation is rather well supported by agreement between measured and calculated permeability.

Finally it is perhaps necessary to consider the blocking occurring in the joint plane formed between two cut surfaces of a porous material when they are randomly rejoined. This model was used by Childs and Collis-George (1950) for their permeability equation. It was later used with equation (1) in a method for obtaining the average neck (or outlet) size when one pore passes into others which are next in the line of movement. In this joint plane the porosity is ϵ^2 and, from this, it might be presumed that a should be equal to ϵ. However this joining process gives a restricted representation of free porosity. Pores considered three-dimensionally have a number of alternative outlets and hence the free porosity of any cross-sectional area is greater than the ϵ^2 of this special plane.

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A TREATMENT OF THE CAPILLARY FRINGE IN THE THEORY OF DRAINAGE

E. C. CHILDS

(*School of Agriculture, Cambridge; and Agricultural Research Council Unit of Soil Physics*)

Summary

The hodograph treatment of the problem of drain design, as developed by van Deemter, is suitably modified to take into account the presence of a capillary fringe above the water table. Examples are presented to show that the presence of the fringe requires an increase of optimum drain size, and that thick fringes are accommodated mostly above a water table which is not proportionately much depressed below that which is appropriate to an absence of fringe, while thin fringes are accommodated in approximately equal proportions above and below the level of the fringeless water table.

THE particular problem in drainage theory which has, perhaps, been studied more intensively than any other is that illustrated in Fig. 1. It is the problem of the location of the water table in semi-infinite soil

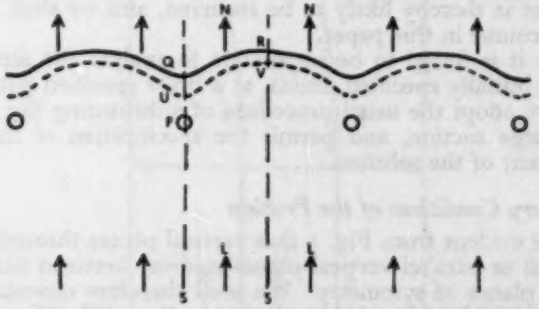

FIG. 1. Diagram showing the elements of the drainage situation considered in this paper.

of uniform hydraulic conductivity K with a uniform flux N across a horizontal surface, when there is a system of artificial drainage consisting of parallel channels of uniform separation $2a$ at uniform depth. It is supposed that the drains are of infinite length compared with their diameter and separation so that the problem is two-dimensional only, the variables being functions of the coordinates in a plane perpendicular to the drain lines. For generality one may suppose also that there is an artesian flux of density L at a depth S sufficiently remote from the drains. If a sufficient time has elapsed since the initiation of the fluxes N and L there will be a steady state with a stationary water table UV and capillary fringe boundary QR so that the flow out of the drains will just equal the net flow *into* the soil due to L and N. It will be assumed that this steady state has been reached. The problem is to determine

at every point in the system the potential and stream functions, and in particular to locate the capillary fringe boundary QR and the water table UV.

Simplifying Assumptions

The path of flow of the water from the soil surface to the drains lies in part in the unsaturated region above the capillary fringe where the hydraulic conductivity is itself a function of the moisture content and hence of the suction and potential, and in part below the capillary fringe boundary where the soil is saturated and at uniform conductivity independent of the potential. The problem of specifying the potential distribution within the genuinely known boundaries is so far intractable, and progress has customarily been made by separate consideration of the saturated zone below QR. This necessitates an assumption of boundary conditions at QR, and it is usual to suppose that the uniformity of flux density N at the soil surface is repeated across a horizontal surface at QR. While this seems reasonable at first sight, it does in fact involve the assumption of the solution of the problem in the space above QR and that the solution provides for vertical streamlines in this space. This assumption is therefore strictly not allowable, but it has been shown by the method of electric analogues (Childs, 1945*b*) that no very serious error is thereby likely to be incurred, and we shall follow this customary course in this paper.

Secondly it is found to be impossible to analyse the actual system comprising initially specified drains, at a finite specified potential, and we therefore adopt the usual procedure of substituting line sinks P at infinitely large suction, and permit the specification of the drain to emerge as part of the solution.

The Boundary Conditions of the Problem

It will be evident from Fig. 1 that vertical planes through the drain axes, as well as parallel vertical planes midway between neighbouring drains, are planes of symmetry. We need therefore consider only the half section $SPQRS$ bounded by the streamlines RS, SP, and PQ and the capillary fringe boundary QR, and this section is isolated in Fig. 2.

We shall first define a potential function ϕ at a point as the work done on a unit *weight* of soil water in moving it from an arbitrary datum at zero height and zero pressure head to that point at height y where the pressure head is h. We then have

$$\phi = y + h. \tag{1}$$

The condition at the water table is that the hydrostatic pressure is just zero, so that ϕ is given by y alone. We are more interested in the fringe boundary, and we adopt again the suggestion (Childs, 1945*a*) that while this boundary is not definable in precise terms and may indeed be elusive, where it is physically evident it may be defined with acceptable approximation as the surface at suction s, characteristic of the soil, at which unsaturation first becomes marked. Because hydraulic permeability decreases so sharply with quite small degrees of unsaturation the

boundary at suction s is a relatively sharp boundary between a lower zone of saturated hydraulic conductivity in which the potential distribution obeys Laplace's equation and an upper zone of relatively low conductivity in which the streaming is predominantly vertical. The boundary conditions at the capillary fringe boundary are therefore

$$\phi_f = y - s \tag{2}$$

and

$$\text{vertical flux density} = N. \tag{3}$$

We shall regard N as positive if upward (net evaporation) and negative if downward (net precipitation).

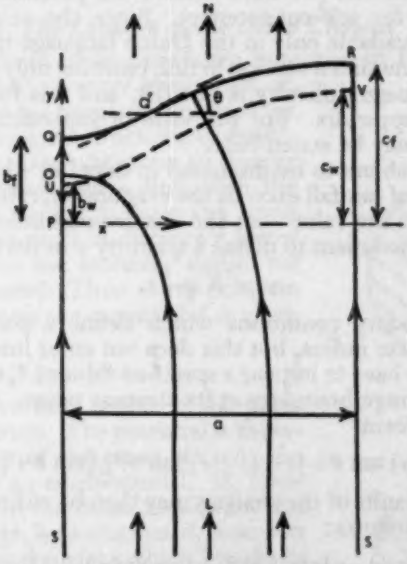

FIG. 2. The boundary conditions of a representative area isolated from Fig. 1.

The boundary condition at great depth S is simply that the flux density is L; this will be positive if upward (net artesian flow) and negative if downward (net percolation). The remaining boundaries are lines of zero transverse flux and the line sink P is by hypothesis at an infinitely large negative potential.

The Hodograph Method

The introduction of the hodograph is now familiar to students of drainage problems. For a general treatment and references to the pioneer work the reader may consult Muskat (1937). The special property which is of value in free surface problems is that while the location of such a surface is initially unknown (indeed such location is usually one of the main objects of the exercise) it becomes a known boundary in a space whose coordinates are the horizontal and vertical

components of the velocity of flow, and is then subject to the various transformations which characterize a typical exercise in potential theory. The diagram in such a space is known as the hodograph.

Our particular problem, but without the complication of the capillary fringe, has been solved by van Deemter (1950). Engelund (1951) has obtained essentially the same results where comparable by a somewhat different series of transformations from a less general hodograph. A further examination of the method has shown that only a slight modification is required to take the capillary fringe into account. In presenting the analysis we shall follow van Deemter, using his nomenclature and symbols where possible (we have defined the potential function somewhat differently for self-consistency). Since the original analysis of van Deemter is available only in the Dutch language there is advantage in setting out the modified version in full, omitting only details of algebra for which a language difficulty is not felt, and this full treatment will be found in an appendix. For purposes of immediate discussion the essential results may be stated here.

The type of problem to be discussed in detail in what follows is that in which the rate of rainfall exceeds the evaporation rate by an amount q, so that N assumes the value $-q$; and the artesian inflow rate L is zero. It proves to be convenient to define a quantity γ in the form

$$\gamma = K/q - 1. \tag{4}$$

Among the boundary conditions which define a particular practical problem is the drain radius, but this does not enter into the problem as stated; instead we have to impose a specified value of θ, the angle of slope of the capillary fringe boundary at its steepest point. A parameter β is expressed in the form

$$(1+\beta) = [(1+\gamma)\tan\theta + \{1+(1+\gamma)^2\tan^2\theta\}^{\frac{1}{2}}]/[\tan\theta + (1+\tan^2\theta)^{\frac{1}{2}}]. \tag{5}$$

The essential results of the analysis may then be written in the form of five equations as follows:

$$\pi c_f/a = \ln(1+2/\beta) + (2/\gamma)\ln(1+\beta/2). \tag{6}$$

Along the boundary RS of Fig. 2

$$\pi y/a = \pi c_f/a + \ln\frac{\delta_a}{\delta_a+2(1+\beta)} + (2/\gamma)\ln\frac{\delta_a+2+\beta}{\delta_a+2(1+\beta)} \tag{7}$$

$$\pi h/a = (q/K)\ln = \frac{\beta+\delta_a}{\delta_a+2+\beta} + \ln\frac{\delta_a+2(1+\beta)}{\delta_a} - \pi s/a \tag{8}$$

for $x = a$; $0 < \delta_a < \infty$.

Along the boundary QP of Fig. 2 we have

$$\pi y/a = \pi c_f/a + \ln\frac{\beta+\delta_b}{2+\beta-\delta_b} + (2/\gamma)\ln\frac{2-\delta_b}{2+\beta-\delta_b} \tag{9}$$

$$\pi h/a = (q/K)\ln\frac{\delta_b}{2-\delta_b} + \ln\frac{2+\beta-\delta_b}{\beta+\delta_b} - \pi s/a \tag{10}$$

for $x = 0$; $0 < \delta_b < 1$.

In equations (6) to (10) c_f is the height of the capillary fringe boundary relative to the origin, midway between neighbouring drain channels; x and y are the horizontal and vertical coordinates respectively of any point specified by an assigned value of δ_a or δ_b, as the case may be, within the stated ranges; and h is the manometric height expressing the value of the hydrostatic pressure at the specified point. A further but less important result is

$$\pi b_f/a = \pi c_f/a - (2/\gamma)\ln(1+\beta), \qquad (11)$$

where b_f is the height of the capillary fringe boundary immediately above a drain channel.

The Location of the Drain Channel

Consider the drain perimeter shown in section in Fig. 3*a*. Let it be supposed to be full of water to the roof, at which point there is a pressure expressed by the manometric height h. Such, for example, might be the case were the drain to emerge at the section shown into a ditch with the water level at a height h above the drain roof. Let the point O at distance r below the drain roof be the arbitrary datum for computing potential. Then at any point on the drain periphery the potential ϕ is given by (1) as

$$\phi = y + (h + r - y) = h + r, \qquad (12)$$

where y is the vertical height of the point chosen above datum. The potential is therefore independent of the point chosen; the drain surface is an equipotential. If, however, the water in the drain falls below the roof, as in Fig. 3*b*, by a distance d, then that part of the channel surface which lies above water level is a surface of seepage at zero pressure provided the channel is wholly below the water table. The potential at any point on the periphery below water level, at height y with respect to the datum, is

$$\phi = y + (r - y - d) = r - d \qquad (13)$$

but above water level is

$$\phi = y. \qquad (14)$$

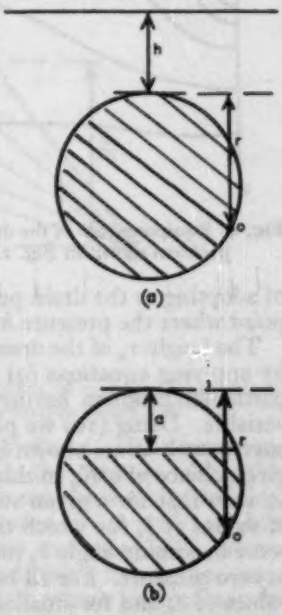

FIG. 3. Boundary conditions at the perimeter of a drain channel (*a*) filled with water to the roof, and (*b*) partially filled.

The drain surface is thus only an equipotential in respect of that portion lying below the level of the water in it. If the drain channel is not wholly below the water table the situation is rather more complicated, for the surface is then in part an equipotential, in part a surface of seepage, and possibly in part a surface at which the suction is a function of the height; but over the last-mentioned portion there will be no entry of water.

The important point is that the drain channel is only an equipotential if the water level in it reaches the roof and the pressure there is zero or greater.

The complete solution of our problem as expressed by equations (51) and (52) of the appendix provides us with the shape of the fringe boundary and the potential distribution within the boundaries; the usual way of depicting this is by means of a set of equipotentials as shown sketched in Fig. 4. Through any point vertically above the line sink, i.e. on PQ, say at height y as given by (9), there will pass an equipotential as shown and the pressure h at this point will be given by (10). It will clearly not affect the potential distribution if this particular equipotential is *imposed*; and the way to impose it is to make it the periphery of a drain whose hydrostatic pressure at the roof is h; and we have seen that this is only possible if h is zero or positive. The particular set of solutions we have arrived at are only valid for such conditions. Since it is usual in practice to avoid 'backing up' the drain, i.e. to permit the development of positive pressures, we shall follow the custom of adopting as the drain periphery that equipotential which cuts PQ at a point where the pressure h is zero.

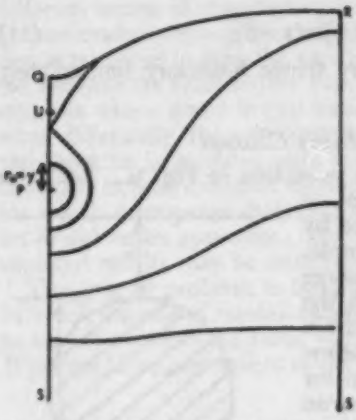

FIG. 4. Equipotentials of the drainage problem shown in Fig. 2.

The height r_0 of the drain roof is found, following the above reasoning, by applying equations (9) and (10). Choice of parameters defining the particular problem having been made, δ_0 remains as the independent variable. Using (10) we plot $\pi(h/a+s/a)$ as a function of δ_0 and obtain curves such as are shown in Fig. 5 for different chosen values of θ for a given choice of q/K; in this diagram θ is increasing from θ_1 to θ_4. It will be seen that for a given value of s/a, not all values of θ permit a range of values of δ_0 for which the hydrostatic pressure h is positive; there is some maximum angle θ_0 for which there is one value of δ_0 corresponding to zero pressure. For all larger values of θ the pressure is negative at all values of δ_0 and for smaller values of θ there are two values of δ_0 corresponding to zero pressure. Using (9) we find $\pi y/a$ corresponding to these values of δ_0 and these, as shown in Fig. 4, give us the points of intersection r_0 and U on PQ of two equipotentials for which the pressures at these intersections are zero. Both of these equipotentials are therefore possible drain perimeters appropriate to the solution. U indicates the upper limit of a zone of positive pressure, and is thus by definition a point on the water table. At the value θ_0 there is only one possible drain perimeter and it passes through the water table at height r_0. At other values of θ it is usual to regard the drain as being reduced in size to r_0 with a consequent rise of water table to U; but it is equally valid

to suppose that we have a larger drain U with a higher water table due simply to the fact that water is, by external control, being retained in it to this greater height. In what follows, however, we shall adopt the former view.

The value of r_u does not suffice by itself to specify the shape and size of the drain equipotential because there is no *a priori* justification for

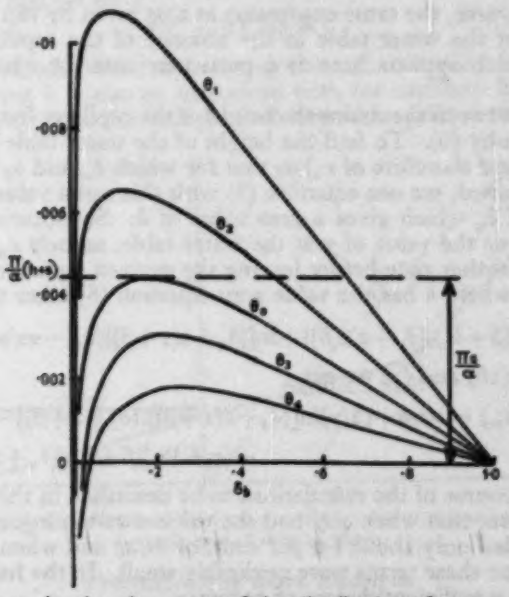

FIG. 5. Curves showing the nature of the distribution of pressure immediately above the drain axis as a function of δ_b, for various values of θ.

supposing this equipotential to be a circle of radius r_u. It is necessary to find the depth of the floor of the drain, i.e. the point at which the equipotential intersects the boundary PS. This may be done by deriving from equations (51) and (52) expressions similar to (9) and (10) but appropriate to PS by substituting for t the variable δ_e+1 where $0 < \delta_e < \beta$. For the same value of θ used for deriving r_u one then may plot h and y versus δ_e and discover those values which simultaneously satisfy the condition obtaining at the floor of the drain, namely

$$h = r_u - y. \qquad (15)$$

However, it is so commonly found from such calculations that the drain equipotential is negligibly different from a circle with centre at the origin that this result is usually assumed, and the value of r_u is tacitly assumed to be the radius of the drain.

The Height of the Water Table and of the Capillary Fringe Boundary

Let us consider first the ordinate of secondary importance, namely that through the drain axis. For a given possible value of θ, defining a

particular drain radius, substitution in (9) of the larger of the two values of δ_b for which h is zero gives us the value of y at the water table, namely b_w. Similarly assigning to δ_b the value unity gives us the value of y at the capillary fringe boundary, namely b_f, in the form

$$\pi b_f/a = \pi c_f/a - (2/\gamma)\ln(1+\beta). \tag{11}$$

This is, of course, the same expression as that given by van Deemter for the height of the water table in the absence of the capillary fringe, a situation which appears here as a particular case for which s has the value zero.

Midway between the drains the height of the capillary fringe boundary is c_f as given by (6). To find the height of the water table for the same value of θ (and therefore of r_u) as that for which b_w and b_f have already been determined, we use equation (8) with this same value of θ to find the value of δ_a which gives a zero value of h. Substitution of this δ_a in (7) gives us the value of y at the water table, namely c_w.

We may further note before leaving the derived equations that at the water table where h has the value zero equation (8) takes the form

$$(q/K)\ln\{(\beta+\delta_a)/(\delta_a+2+\beta)\}+\ln[\{\delta_a+2(1+\beta)\}/\delta_a]-\pi s/a = 0. \tag{16}$$

Combining (16) and (7) we get

$$(\pi/a)(c_f-c_w) = \pi s/a+(2/\gamma)\ln[\{\delta_a+2(1+\beta)\}/(\delta_a+2+\beta)]- \\ -(q/K)\ln\{(\beta+\delta_a)/(\delta_a+2+\beta)\}. \tag{17}$$

During the course of the calculations to be described in the next section it became clear that when q/K had the value 0·01 the logarithmic terms of (17) totalled only about 1·0 per cent. of $\pi s/a$; and when the value of q/K was 0·001 these terms were negligibly small. In the former case we can write to a sufficient degree of accuracy

$$(c_f-c_w) = 1{\cdot}01s \tag{18}$$

and in the latter case

$$(c_f-c_w) = s. \tag{19}$$

This conclusion is supported by the following elementary argument. The flow of water q per unit cross-section through a vertical column of porous material whose hydraulic conductivity in the saturated state is K_{sat} and whose lower end dips beneath a free water surface to a depth D is in accordance with the potential distribution illustrated in Fig. 6 in which the free water surface is taken arbitrarily to be the zero of potential. The line $\phi = y$, where y is vertical height as before, satisfies the condition of zero pressure, while the parallel line, also with slope 45°, $\phi = y-s$ satisfies the condition at the boundary of the capillary fringe, where the pressure is $-s$. The potential distribution is as indicated by the line *ABCE* (Childs, 1945*b*), where *ABC* is a straight line of slope $\lambda°$ where, by Darcy's law,

$$q/K_{sat} = d\phi/dy = \tan\lambda. \tag{20}$$

This follows because the material is saturated at all pressures in excess of

$-s$ by our definition of the capillary fringe. It is easily shown by geometrical arguments that

$$BF = s(1+\tan\lambda+\tan^2\lambda+\ldots)$$

where BF is, as shown, the thickness of the capillary fringe. When $\tan\lambda$, i.e. q/K, is less than 0·1 it is sufficiently accurate to omit terms beyond $\tan\lambda$, and we have

$$BF = s(1+q/K). \qquad (21)$$

This is in agreement with (18) and (19) above, and it will emerge in the next section that it is also in agreement with the capillary fringe thickness as calculated from the hodograph theory when q/K has the value 0·1.

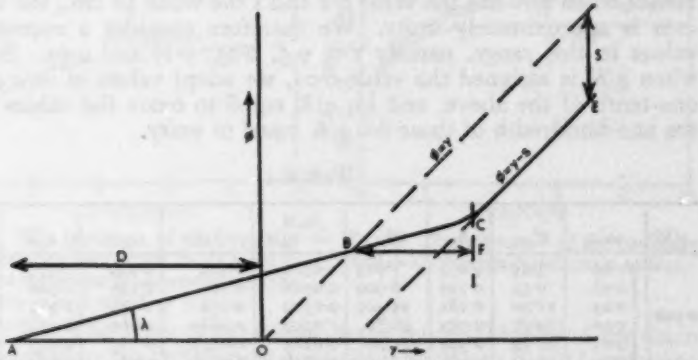

FIG. 6. The potential distribution along a vertical column of porous material with a steady rate of flow of water.

Presentation of Some Examples

Considerable space would be required for the presentation of calculations covering combinations of ranges of capillary fringe suction, drain radius, and values of q/K. We shall confine our examples, therefore, to cases of optimum drain radius, i.e. to such values of θ as provide only one possible drain radius.

In selecting values of q/K we may bear in mind that this parameter may be as small as 0·001, a value which is common in irrigation practice where the water applied in excess of consumptive use is controlled and is permitted to be no more than is required to ensure the non-accumulation of salt. If, on the other hand, q/K reaches the value unity then the water table must inevitably reach the surface in spite of the presence of the drainage system. We therefore assign to q/K the successive values 0·1, 0·01, and 0·001.

We next consider possible values of s. In those cases where a capillary fringe is distinctly recognizable and has a reasonably well defined thickness, this thickness is not commonly much in excess of 50 cm. We therefore adopt this as the maximum value of s to be treated here. The fringe thickness appears in the theory in the form of the parameter s/a, and we need therefore to consider appropriate values of a, using the

following rough guide. The water-table height c in the absence of a capillary fringe is given by c_f of (6) if β is assigned the value γ. Engelund (loc. cit.) has presented a curve showing how this height varies with q/K, and over the range we are considering we may write with sufficient accuracy for our present purpose

$$c/a = 3q/K.$$

If we adopt as our drainage requirement, consistent with a usual depth of drain channel of 100 to 150 cm., that c should not be allowed to exceed 50 cm. then we have

$$a = 16{\cdot}7/(q/K) \text{ cm.}$$

Hence when q/K has the value 0·1 and s the value 50 cm., the value of $\pi s/a$ is approximately unity. We therefore consider a succession of values in this range, namely 1·0, 0·5, 0·25, 0·1, and 0·05. Similarly when q/K is assigned the value 0·01, we adopt values of $\pi s/a$ equal to one-tenth of the above, and for q/K equal to 0·001 the values of $\pi s/a$ are one-hundredth of those for q/K equal to unity.

TABLE 1

q/K	$\pi s/a$	$\theta°_{opt.}$	δ_b	δ_a	$b_w/a = r_0/a$	b_f/a	c_w/a	c_f/a	$(c_f-c_w)/s$
0·100	1·00	3·25	0·053	1·713	0·0320	0·443	0·129	0·477	1·09
	0·50	6·55	0·105	6·900	0·0318	0·261	0·146	0·322	1·11
	0·25	11·30	0·181	23·400	0·0319	0·158	0·159	0·247	1·11
	0·10	19·75	0·295	96·80	0·0297	0·0889	0·169	0·204	1·11
	0·05	27·60	0·395	245·20	0·0283	0·0617	0·175	0·193	1·11
	0·00	90·00	1·000	..	0·0216	0·0216	0·184	0·184	1·11
0·010	0·100	4·317	0·073	..	0·00311	0·0413	0·0262	0·0583	1·01
	0·050	7·433	0·123	..	0·00305	0·0236	0·0275	0·0437	1·01
	0·025	11·75	0·190	..	0·00297	0·0145	0·0292	0·0372	1·01
	0·010	20·30	0·312	..	0·00280	0·00802	0·0302	0·0334	1·01
	0·005	27·70	0·397	..	0·00260	0·00568	0·0307	0·0324	1·01
	0·000	90·00	1·000	..	0·00197	0·00197	0·0316	0·0316	
0·001	0·0100	4·35	0·079	..	0·000334	0·00408	0·00405	0·00723	1·00
	0·0050	7·35	0·126	..	0·000311	0·00237	0·00423	0·00582	1·00
	0·0025	11·70	0·189	..	0·000296	0·00145	0·00436	0·00516	1·00
	0·0010	20·00	0·307	..	0·000275	0·000805	0·00446	0·00478	1·00
	0·0005	28·50	0·411	..	0·000257	0·000541	0·00451	0·00467	1·00
	0·0000	90·00	1·000	..	0·000197	0·000197	0·00460	0·00460	..

For each combination of values of q/K and $\pi s/a$ one may calculate for optimum θ the values of b_w/a (equal to r_0/a), b_f/a, c_w/a, and c_f/a. The results are presented in Table 1. In this table column 5 is left blank for the two smaller values of q/K because δ_a was not in fact calculated. Instead equations (18) and (19) respectively were used to calculate the values in column 8 from those in columns 9 and 10. For the highest value of q/K columns 8 and 9 were evaluated from equations (6), (7), and (8), and column 10 followed. These last figures are in fair agreement with (21) and even better agreement with the equation from which it is derived with the term $\tan^2\lambda$ retained.

The relationship between the heights of the water table, the upper

boundary of the capillary fringe, and the water table in the absence of a capillary fringe (i.e. when s has the value zero) is shown most clearly by Fig. 7. In this are plotted the functions $(c_f-c)/s$ and $(c_w-c)/s$ where c is the value equally of c_f and c_w in the absence of the capillary fringe. These functions are plotted against the variable

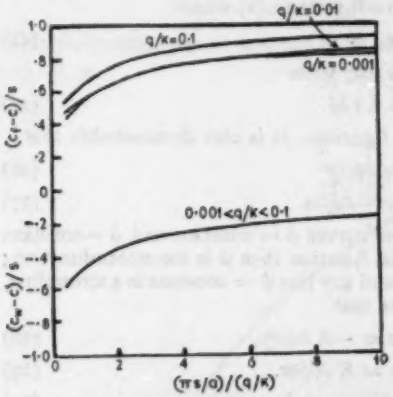

FIG. 7. The positions of the capillary fringe boundary and of the water table in relation to the water table position in the absence of a capillary fringe.

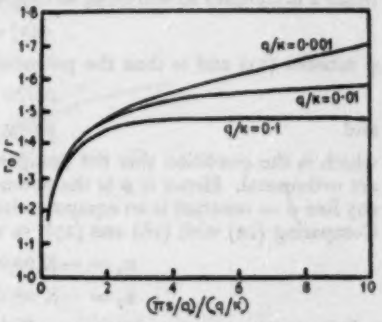

FIG. 8. The influence of the capillary fringe on the optimum drain radius.

$(\pi s/a)/(q/K)$. The effect of the fringe on the required radius of the drain channel to secure the optimum water table is shown in Fig. 8 by plotting the function r_0/r, where r is the optimum drain radius in the absence of the capillary fringe. The general effect seems to be the same at all values of q/K, namely that for thick fringes the bulk of the thickness is accommodated above a water table which is not much depressed in proportion below the level appropriate to the absence of a fringe, although in absolute terms, of course, as is plain from column 8 of Table 1, the thicker the fringe the lower is the water table. For thin fringes, on the other hand, the fringe is accommodated in roughly equal amounts above and below the level of the fringeless water table. The optimum drain radius increases by about 50 per cent. at the maximum fringe thickness for all values of q/K. The most striking effect here is the large increase of r_0 for very thin capillary fringes.

APPENDIX

The Equations of Flow

If v is the velocity of flow of water in the porous medium whose hydraulic conductivity is K, then Darcy's law is expressed in the equation

$$v = -K \operatorname{grad} \phi. \qquad (22)$$

v is measured in units of volume per second across unit area perpendicular to the direction of flow. The equation of continuity, which expresses the fact that in a saturated medium accommodating the flow of an incompressible liquid the rate of flow into an element of volume must equal the rate of flow out, is the well-known

equation of Laplace, which for two dimensions is

$$\partial^2\phi/\partial x^2+\partial^2\phi/\partial y^2 = 0 \tag{23}$$

x and y are the horizontal and vertical coordinates respectively with P as the origin, as shown in Fig. 2. It is shown in the standard texts (see, for example, Jeans, *Magnetism and Electricity*, 1933, Oxford University Press) that the most general solution of this equation is obtained from a function $\omega(z)$ where

$$z = x+iy \tag{24}$$

Since z is complex so will be ω, so that we may write

$$\omega(z) = \phi+i\psi \tag{25}$$

ϕ satisfies (23) and is thus the potential function. It is also demonstrable that

$$\partial\phi/\partial x = \partial\psi/\partial y \tag{26}$$

and

$$\partial\phi/\partial y = -\partial\psi/\partial x \tag{27}$$

which is the condition that the families of curves $\phi =$ constant and $\psi =$constant are orthogonal. Hence if ϕ is the potential function then ψ is the streamfunction; any line $\phi =$ constant is an equipotential and any line $\psi =$ constant is a streamline. Comparing (22) with (26) and (27) we see that

$$v_x = -K\,\partial\phi/\partial x = -K\,\partial\psi/\partial y, \tag{28}$$

$$v_y = -K\,\partial\phi/\partial y = K\,\partial\psi/\partial x. \tag{29}$$

Let us write

$$w = -K\,d\omega/dz = u+iv. \tag{30}$$

It is shown in the standard texts on functions of the complex variable that differentiation with respect to z is, if possible at all, the same as differentiation with respect to the real part of z, namely x, so

$$w = -K(\partial\phi/\partial x+i\,\partial\psi/\partial x)$$

and combining with (27) we have

$$w = -K(\partial\phi/\partial x-i\,\partial\phi/\partial y). \tag{31}$$

Comparing this with (28) and (29) we have

$$w = v_x-iv_y$$

so that, from (30),

$$\left.\begin{aligned} u &= v_x \\ v &= -v_y \end{aligned}\right\}. \tag{32}$$

Now the hodograph is the diagram in which the coordinates are v_x and v_y, so that the w-plane may be taken as representing the hodograph if we remember that the vertical velocity is reversed in sign.

The Boundaries in the Hodograph Plane

The capillary fringe boundary is the only one which is not self-evident in the hodograph. A portion of it is depicted in Fig. 9; at a point where the slope is α we have horizontal and vertical flow velocity components v_x and v_y respectively. Let distance measured along the fringe boundary be l, and other quantities measured in this direction be indicated by the subscript l. Then we have

$$v_l = v_x\cos\alpha+v_y\sin\alpha.$$

Using (22) and (32) we thus have

$$-K(\partial\phi_l/\partial l) = -K(\partial\phi_l/\partial y)\sin\alpha = u\cos\alpha-v\sin\alpha.$$

Differentiating (2) gives us

$$\partial\phi_l/\partial y = 1$$

so that finally our capillary fringe condition above becomes

$$-u\cos\alpha+v\sin\alpha = K\sin\alpha. \tag{33}$$

Similarly we may obtain a relationship for the component of flux, v_n, normal to the fringe boundary. This relationship is, as may be seen from Fig. 9,

$$v_n = v_y\cos\alpha - v_x\sin\alpha,$$

where the positive sign is assigned to an outward flux. The flux per unit horizontal area, N, is

$$N = v_n/\cos\alpha$$

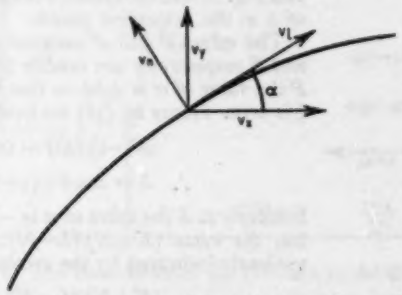

FIG. 9. Components of the velocity of flow of soil water at the capillary fringe boundary

hence the fringe relationship is, again using (32)

$$-u\sin\alpha - v\cos\alpha = N\cos\alpha. \tag{34}$$

Equations (33) and (34) may be written

$$\tan\alpha = -u/(K-v) = -(N+v)/u \tag{35}$$

and eliminating α we get

$$u^2+\{v-(K-N)/2\}^2 = \{(K+N)/2\}^2. \tag{36}$$

This is the equation of the circle shown in the hodograph, Fig. 10, with centre at the point $(O, i[K-N]/2)$ and radius $(K+N)/2$; it cuts the v-exis at the points iK and $-iN$. By (35) the angle of slope at a point on the boundary is equal to the angle subtended at iK in the hodograph by the arc of the circle between the corresponding point on the hodograph and the point $-iN$. By symmetry the fringe boundary is horizontal at O and R, i.e. θ is zero. This locates the corresponding points on the hodograph at $(0, -iN)$. The steepest angle of slope θ defines the extent of the arc of the circle in the hodograph, as shown.

At all other boundaries the flow velocity is vertical; it is of magnitude L at S and changes from $+\infty$ to $-\infty$ at P. The hodograph or w-plane is thus readily completed as shown; the points corresponding to those of Fig. 2 are indicated by the letters to the left and the values of w by the symbols to the right at each point. It will be noted that this hodograph is identical with that for the case considered by van Deemter, where the water table was the boundary. The reason is, of course, that the boundary equation (2) enters into the derivation only in its differentiated form, in which the constant s which distinguishes the capillary fringe from the water table disappears.

Conformal Transformation of the Hodograph

Following van Deemter we make the following successive transformations or definitions of new variables ζ and σ:

$$\zeta = (K+N)/(-N+iw) \tag{37}$$

$$\zeta = \tfrac{1}{2}\{(\sigma-1)/\sigma^{\frac{1}{2}}\}\cot\theta - 1. \tag{38}$$

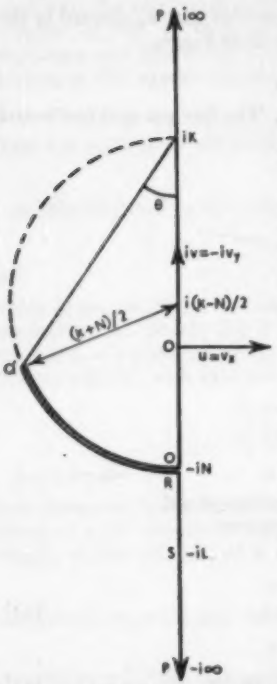

FIG. 10. The boundaries of the problem shown in Fig. 2 as drawn in the hodograph plane.

The boundary of the problem in the intermediate ζ plane is shown in Fig. 11 and in the σ plane is, as shown in Fig. 12, the real axis. The letters below the line indicate the points of correspondence with Fig. 2 and Fig. 10 and the symbols above indicate the values of σ at the respective points.

The values λ^2 and μ^2 assigned to σ at the points P and S respectively are readily found as follows. At P the value of w is $\pm i\infty$ so that by (37) the value of ζ is zero. Hence by (38) we have

$$(\lambda^2-1)/(2\lambda) = \tan\theta$$

$$\therefore\quad \lambda = \tan\theta + (1+\tan^2\theta)^{\frac{1}{2}}. \tag{39}$$

Similarly at S the value of w is $-iL$ so that by (37) ζ has the value $(K+N)/(L-N)$; this ratio is conveniently indicated by the symbol γ. Thus

$$(K+N)/(L-N) = \gamma \tag{40}$$

and by (38) we have

$$(\mu^2-1)/(2\mu) = (1+\gamma)\tan\theta$$

$$\therefore\quad \mu = (1+\gamma)\tan\theta + \{1+(1+\gamma)^2\tan^2\theta\}^{\frac{1}{2}} \tag{41}$$

and $$\frac{\mu}{\lambda} = \frac{(1+\gamma)\tan\theta + \{1+(1+\gamma)^2\tan^2\theta\}^{\frac{1}{2}}}{\tan\theta + (1+\tan^2\theta)^{\frac{1}{2}}}.$$

The limiting value of μ/λ when θ has the value 90° is thus $(1+\gamma)$ and we shall find it convenient to define a quantity β for other values of θ such that

$$\mu/\lambda = (1+\beta) \tag{42}$$

so that finally

$$\mu/\lambda = (1+\beta) = \frac{(1+\gamma)\tan\theta + \{1+(1+\gamma)^2\tan^2\theta\}^{\frac{1}{2}}}{\tan\theta + (1+\tan^2\theta)^{\frac{1}{2}}}. \tag{5}$$

Although we do not refer further in this paper to point O where σ has the value ν^2, we may for later reference and for completeness derive ν/λ in a similar manner to get

$$\frac{\nu}{\lambda} = \frac{-(K/N)\tan\theta + \{(K/N)^2\tan^2\theta+1\}^{\frac{1}{2}}}{\tan\theta + (1+\tan^2\theta)^{\frac{1}{2}}}. \tag{5a}$$

Transformation of the Complex Potential

We first define a variable Ω in the form

$$\Omega = \omega - iNx/K = \phi + Ny/K + i(\psi - Nx/K). \tag{43}$$

The diagram of the problem boundaries in the Ω-plane is shown in Fig. 13 where again point correspondence is indicated below the line and Ω values above. At O and R the values of ϕ are given by (2) where γ has the value b_f and c_f respectively;

ψ is evaluated by the elementary integration of (29) with v_y equal to N along QR and L at S.

The transformation $$\eta = \exp.[-(\pi\Omega K)/\{a(L-N)\}] \tag{44}$$ produces the half-plane shown in Fig. 14 of which the problem boundary is the real axis. The two half-planes σ and η may then be brought into coincidence by the transformation

$$\eta = \{(\sigma-\mu^2)/(\sigma-\lambda^2)\}\exp.[-\pi\gamma c_f/a+\pi Ks/\{a(L-N)\}]. \tag{45}$$

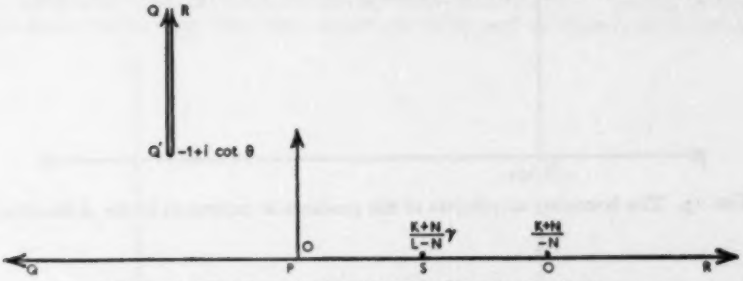

FIG. 11. The boundaries of the problem in the ζ plane.

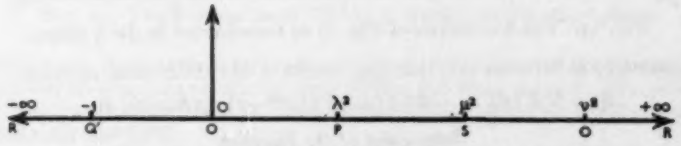

FIG. 12. The boundaries of the problem in the σ plane.

This transformation may be checked at P, S, and R by confirming that values of σ and η from Figs. 12 and 14 satisfy (45). The correspondence at Q provides, from (45), the relationship

$$\exp.[-\pi\gamma b_f/a+\pi Ks/\{a(L-N)\}] = (\mu^2/\lambda^2)\exp.[-\pi\gamma c_f/a+\pi Ks/\{a(L-N)\}].$$

With the aid of (42) we can readily reduce this to

$$\pi b_f/a = \pi c_f/a-(2/\gamma)\ln(1+\beta). \tag{11}$$

This is the first element of the solution to emerge.

A final transformation in the interests of subsequent computation is

$$t = \sigma^{\frac{1}{2}}/\lambda \tag{46}$$

and this plane is shown in Fig. 15. The boundary corresponding to the capillary fringe is the positive imaginary axis and the remainder of the boundary is the positive real axis.

The Differential Equation of the Problem

The successive transformations (44), (45), and (46) are equivalent to the single overall transformation

$$\Omega = c_f(K+N)K-s-\{(a/\pi)(L-N)/K\}\ln\{(t^2-\mu^2/\lambda^2)/(t^2-1)\}. \tag{47}$$

The successive transformations (37), (38), and (46) are equivalent to the single overall transformation

$$w = -i\{N+(K+N)/[\{(\lambda^2 t^2-1)/(2\lambda t)\}\cot\theta - 1]\}. \tag{48}$$

Equations (30) and (43) give us

$$w = -K(d\Omega/dz + iN/K). \tag{49}$$

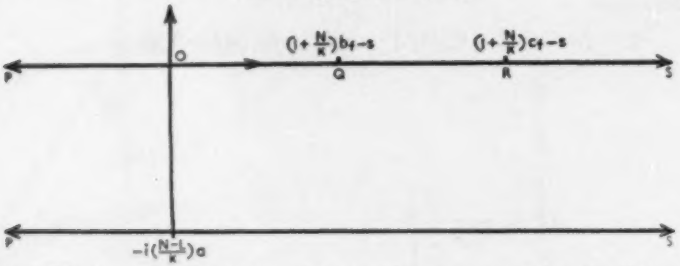

FIG. 13. The boundary conditions of the problem as expressed in the Ω function.

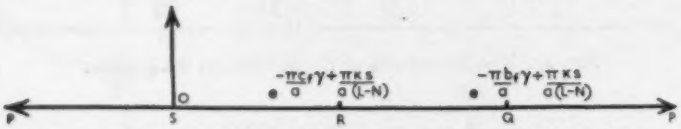

FIG. 14. The boundaries of Fig. 13 as transformed in the η plane.

Elimination of w between (48) and (49) results in the differential equation

$$i(1+N/K)\,dz = -d\Omega+(d\Omega/dt)\{(\lambda^2 t^2-1)\cot\theta/(2\lambda t)\}\,dt. \tag{50}$$

Integration of the Equation

We may find an expression for $d\Omega/dt$ by differentiating (47), and upon substituting this in (50) the latter equation may be integrated to yield

$$z = x+iy = a+ic_1+(ia/\pi)\left\{\ln\frac{t-1-\beta}{t+1+\beta}+(2/\gamma)\ln\frac{t+1}{t+1+\beta}\right\}. \tag{51}$$

With z known from (51) and Ω from (47) it is a matter of straightforward substitution in (43) to find ω. The result is

$$\omega = \phi+i\psi = c_1-s+iNa/K+\{a/(\pi K)\}[(L-N)\ln(t-1)-L\ln(t-1-\beta)+$$
$$+N\ln(t+1+\beta)+\{(L-N)(K-N)/(K+N)\}\ln\frac{t+1}{t+1+\beta}]. \tag{52}$$

Equations (51) and (52) constitute the solution of the problem. Adoption of values of K, L, N, s, and θ amounts to the specification of a particular problem; γ is then determinable from (40) and β from (5). The selection of a value of t, which may, of course, be complex but must lie in the quadrant of Fig. 15, then amounts to the selection of a point (x, y) which may be determined by equating separately the real and imaginary terms of (51); and substitution of this same value of t in (52) gives us the potential and streamfunctions at this point. Our solution differs from van Deemter's only by the inclusion of the term $-s$ in (52).[1] To appreciate the extent

[1] It would follow directly since any constant potential term may be added without affecting the flow.

of the generalization which this added term confers, we need to examine a specific problem quantitatively.

Drainage without Artesian Inflow

As a particular problem we shall consider the case where L has the value zero and there is net precipitation q at the surface, so that N has the value $-q$. From (40) we then have

$$\gamma = K/q - 1. \tag{4}$$

Among the many features of the problem we are primarily interested in the height of the capillary fringe boundary, c_f, and the water-table height, c_w, midway between the drains where these have their maximum value, and secondarily in b_f and b_w,

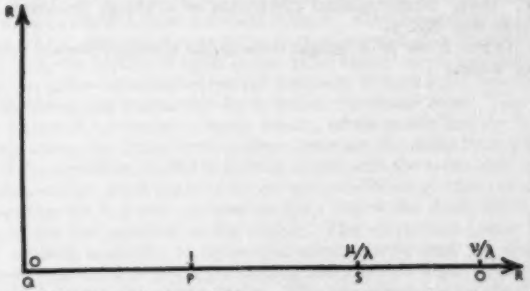

FIG. 15. The boundaries of Fig. 12 as transformed in the t plane.

the fringe and water-table heights respectively immediately over the drains. These values will be functions of, among other things, the drain radius r. The points we shall require to concentrate on, therefore, are those which lie on the boundary portions RS and QPS.

Reference to Fig. 15 shows that along RS the value of t is real and lies between $(1+\beta)$ and ∞; while along QP the value of t is real and lies between zero and unity. We may conveniently choose new variables

$$\left.\begin{aligned} \delta_a &= t-(1+\beta) \\ \delta_b &= 1-t \end{aligned}\right\}. \tag{53}$$

Substituting for ϕ in (52) by the use of (1), and making use of (4), equations (51) and (52) yield the following forms which are well suited to numerical computation. For the boundary RS

$$\pi y/a = \pi c_f/a + \ln \frac{\delta_a}{\delta_a+2(1+\beta)} + (2/\gamma)\ln \frac{\delta_a+2+\beta}{\delta_a+2(1+\beta)} \tag{7}$$

$$\pi h/a = (q/K)\ln \frac{\beta+\delta_a}{\delta_a+2+\beta} + \ln \frac{\delta_a+2(1+\beta)}{\delta_a} - \pi s/a \tag{8}$$

$$x = a; \qquad 0 < \delta_a < \infty.$$

For the boundary QP

$$\pi y/a = \pi c_f/a + \ln \frac{\beta+\delta_b}{2+\beta-\delta_b} + (2/\gamma)\ln \frac{2-\delta_b}{2+\beta-\delta_b} \tag{9}$$

$$\pi h/a = (q/K)\ln \frac{\delta_b}{2-\delta_b} + \ln \frac{2+\beta-\delta_b}{\beta+\delta_b} - \pi s/a \tag{10}$$

$$x = 0; \qquad 0 < \delta_b < 1.$$

The value of $\pi c_f/a$ follows at once from (41) if we consider the point P, where y and δ_b are known to have the values zero. These substitutions give

$$\pi c_f/a = \ln(1+2/\beta)+(2/\gamma)\ln(1+\beta/2). \tag{6}$$

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WATER-TABLE HEIGHTS IN A DRAINED HOMOGENEOUS SOIL OVERLYING AN INFINITELY PERMEABLE LAYER

E. G. YOUNGS

(*Agricultural Research Council Unit of Soil Physics, Huntingdon Road, Cambridge*)

Summary

Drainage investigations in the past have been mostly concerned with soils which are infinitely deep or which overlie impermeable beds, and little attention has been paid to soils which overlie a more permeable layer. Electric-analogue experiments are described which give solutions to the particular case of a homogeneous soil, drained by a uniform system of ideal drain tubes and overlying an infinitely permeable layer, for different ratios of rainfall intensity to hydraulic conductivity and for various depths of the permeable layer below the drain level. The results are presented in terms of a correction factor which, when multiplied by the height of the water table above the drain level midway between the drain lines which would be observed if the topsoil extended to infinite depth with the same ratio of rainfall to hydraulic conductivity, gives the maximum water-table height for a given depth of boundary between the soil and permeable layer below the drain level, expressed as a fraction of the half-spacing of the drains. The correction factor varies with the ratio of rainfall intensity to hydraulic conductivity and the depth of the permeable layer below the drain, approaching unity as this depth increases beyond one-third of the half-spacing of the drains. The correction factor obtained here is compared with that obtained for the case of the soil overlying an impermeable bed for the values of the ratio of rainfall intensity to hydraulic conductivity of 0·01, 0·02, 0·05, and 0·10. The two sets of results represent the extreme cases of water-table heights which can be observed in a two-layered soil with the drain laid in the top layer.

In a recent communication (Collis-George and Youngs, 1958) the water-table heights in a drained homogeneous soil overlying an impermeable floor were discussed in relation to the drain design dimensions, rainfall intensity, and hydraulic conductivity. It was shown that in such cases the water table was lowered as the depth of impermeable floor below the drain was increased, other factors remaining unchanged. Soil profiles occur often to fit this case with sedimentary soils overlying clay strata. Less commonly considered in drainage work is the occurrence of a more permeable layer of soil (which itself does not drain to a sink) lying embedded below the topsoil.[1] The proximity of such more permeable layers to the drains is a determining factor on the water-table heights in a drained soil.

The complete solution to such a problem would be to investigate the effect on water-table heights for different thicknesses of layer of varying hydraulic conductivity at different depths below the drains. However, we are more concerned here to find out the general effect of such layers rather than to obtain solutions to fit all cases. The greatest effect such a layer can have is the extreme case of an infinitely permeable layer underlying the homogeneous soil of given hydraulic conductivity. This

[1] The author is indebted to Mr. A. N. Ede of this laboratory for indicating the practical implications of this investigation.

is approximated to in the case of a gravel deposit in a silty soil. Such a layer acts as a short circuit to water flow.

Such an investigation is easily carried out in an electric analogue (Childs, 1943). In the work reported here the technique used was that reported by Collis-George and Youngs (1958) with 'Teledeltos' graphited paper used as the conducting sheet with variable width strips conducting the current to the 'water table'. The short circuiting very permeable layer was represented in the analogue by a brass bar of $\frac{1}{4}$ in. square cross-section which was cemented to the paper with 'Aquadag' colloidal graphite, during the drying of which pressure was applied to ensure good contact between the brass bar and conducting paper. Good contact was confirmed by the fact that a constant electrical potential was found throughout the conducting paper which was cut off from the supplying terminals by the short-circuiting bar. In the analogue the half-spacing D of the drain tubes was 20 cm. and the drain diameter 0·8 cm.

The analogue was constructed (Childs, 1943) for given values of h/D for various values of d/D, where h and d are respectively the height of the water table midway between the drain tubes and the depth of the permeable layer, measured relative to the drain axis. The value of the ratio of rainfall intensity to hydraulic conductivity q/K was determined from the electrical and dimensional properties of the analogue from the relationship (Collis-George and Youngs, 1958)

$$q/K = h_e/V_0 \operatorname{grad} V, \tag{1}$$

where h_e was the height of the 'water table' midway between the drain tubes above the top of the drain terminal in the analogue, V_0 the electrical potential at this point relative to that of the drain terminal, and grad V the potential gradient down the conducting strips of 'Teledeltos' paper measured with the potentiometer.

It is convenient to present these experimental results in the form of a correction factor h/h_∞, where h_∞ is the water-table height midway between the drains when the soil extends to infinite depth, so that the height of the water table h can be obtained by multiplying the theoretically obtained h_∞ (van Deemter, 1950; Engelund, 1951) by this factor. This is shown in Fig. 1 in which h/h_∞ is plotted as a function of d/D for values of q/K of 0·01, 0·02, 0·05, and 0·10. These are to be compared with the values given in the previous communication (Collis-George and Youngs, 1958) for soil overlying an impermeable floor, given in the inset of Fig. 1. Unlike the case of the soil above an impermeable floor, the effect of a more permeable layer becomes more pronounced as q/K is increased. It is observed, for example, that for $q/K = 0{\cdot}01$ the correction factor h/h_∞ is 0·9 at $d/D = 0{\cdot}1$ for the case of the permeable layer where it was 1·7 in the case of the impermeable floor, while for $q/K = 0{\cdot}1$ the comparison is 0·62 to 1·2 with the same value of d/D. In all cases the value of the correction factor approaches unity as d/D becomes greater.

The two cases compared apply to a two-layered soil with the lower layer on the one hand of infinite and on the other hand of zero hydraulic

conductivity. It is of interest to consider the intermediate cases when the soil of the lower layer has a finite hydraulic conductivity between infinity and zero. If it is more permeable than the soil of the top layer, the water-table height has a value which lies between that obtained when the soil overlies an infinitely permeable layer at the same boundary

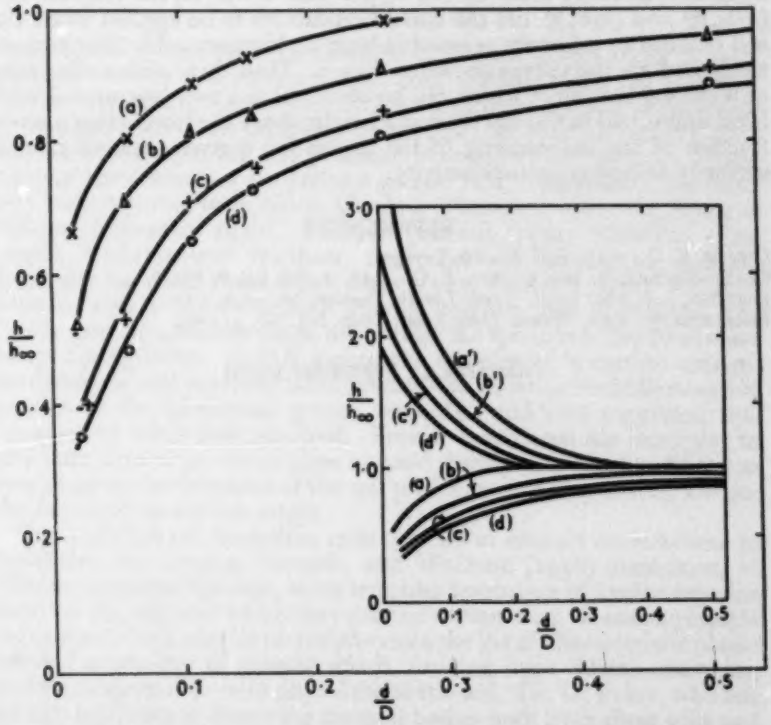

FIG. 1. Variation of the correction factor h/h_∞ with d/D for a homogeneous soil, drained by a uniform system of ideal drains, overlying an infinitely permeable bed. *Inset*: Comparison with the case of a soil overlying an impermeable bed.

(*a*) $q/K = 0{\cdot}01$, (*b*) $q/K = 0{\cdot}02$, (*c*) $d/K = 0{\cdot}05$, and (*d*) $q/K = 0{\cdot}10$ for the case of the soil overlying an infinitely permeable bed. (*a'*), (*b'*), (*c'*), and (*d'*) the same as for (*a*), (*b*), (*c*), and (*d*) but for the case of the soil overlying an impermeable bed.

depth and that obtained if the topsoil extended to infinite depth, other factors remaining unchanged. Similarly, if the soil of the lower layer is less permeable than that of the top layer, the water-table height has a value which lies between that obtained when the soil overlies an impermeable floor at the same boundary depth and that obtained if the topsoil extended to infinite depth. If K_1 and K_2 are the hydraulic conductivities of the soils of the top and lower layers respectively, then the above can be written as follows:

$$\left.\begin{array}{ll} K_2 > K_1, & (h/h_\infty)^{K_1}_{\infty} < (h/h_\infty)^{K_1}_{K_2} < 1 \\ K_2 = K_1, & (h/h_\infty)^{K_1}_{K_2} = 1 \\ K_2 < K_1, & (h/h_\infty)^{K_1}_{0} > (h/h_\infty)^{K_1}_{K_2} > 1 \end{array}\right\}, \qquad (2)$$

where the superscripts and subscripts outside the brackets indicate the hydraulic conductivities of the upper and lower layers respectively. $(h/h_\infty)^{K_1}_{\infty}$ and $(h/h_\infty)^{K_1}_{0}$ are the correction factors to be applied when the soil overlies an infinitely permeable layer and impermeable floor respectively and are the curves shown in Fig. 1. Thus these define the limits of water-table heights which can be observed in a two-layered soil with ideal drains laid in the top layer at a height above the lower layer a given fraction of the half-spacing of the drains for a given ratio of rainfall intensity to hydraulic conductivity.

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OPAL SPONGE SPICULES IN SOILS

F. SMITHSON
(*University College of North Wales, Bangor*)

Introduction

MANY kinds of opaline silica particles of organic origin occur in soils, and their sources can be determined with various degrees of accuracy. For diatoms, specific identifications have long been possible in the hands of specialists; for grass phytoliths, although it is nearly a century since they were first reported, less precision is possible; and for opal sponge spicules[1] the difficulties are perhaps greater still. Examples of the latter have been reported from North Carolina (Plummer, 1915–16), Java and Malaya (Scrivenor, 1930), Australia (Carroll, 1932; Nicholls, 1936; Leeper, Nicholls, and Wadham, 1936; Brewer, 1955, 1956; Leeper, 1955), and Russia (Tyurin, 1937; Usov, 1943; Yarilova, 1956). All three Russian writers observed both sponge spicules and phytoliths, and Tyurin gave detailed drawings, attributing the spicules to the freshwater group, Spongillidae. Carroll mentioned spicules of 'a marine sponge-like *Ecionema*' and regarded them as wind-borne, while Nicholls recorded spicules of the freshwater genus, *Spongilla*, and also suggested that transport by wind had occurred. Brewer considered his examples to have been formed *in situ* or close at hand during very wet conditions at some stage of development of the soil profile, a view disputed by Leeper who favoured an aeolian origin.

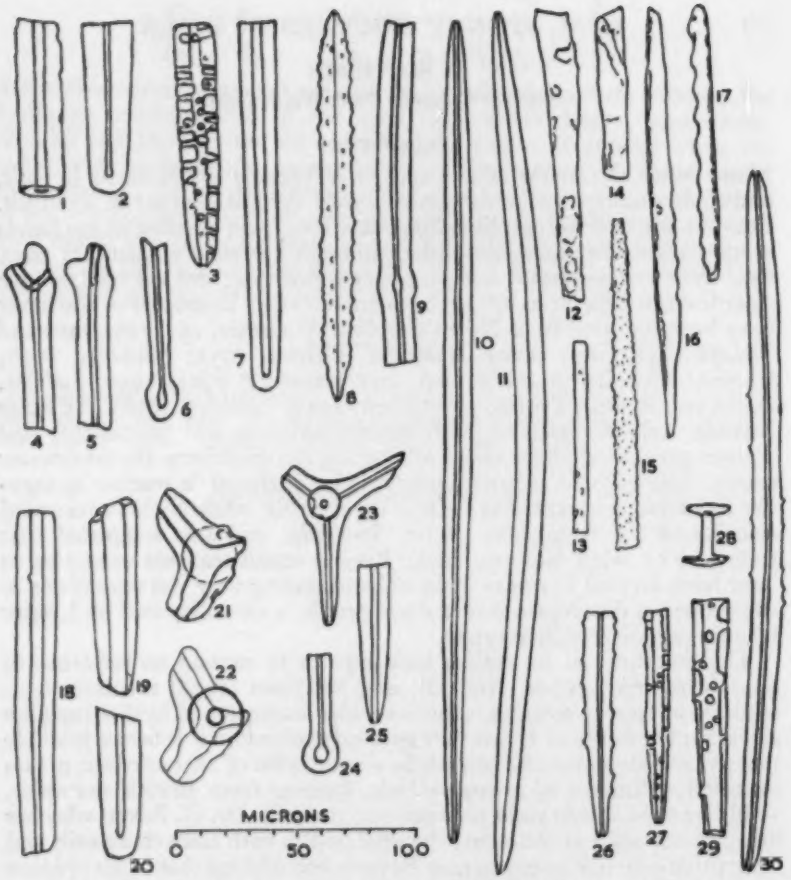
The literature on Australian soils appears to contain no reference to phytoliths, but Leeper, Nicholls, and Wadham (1936) mentioned, in addition to sponge spicules, some irregular fragments of hyalite (opaline silica) for the origin of which they gave no explanation. It seems possible that some of these may be phytoliths since the list of characteristic plants included a number of grasses which, judging from British examples, would be expected to yield phytoliths to the soil. Dr. G. Baker, who has had opportunities of observing the opal bodies both from these soils and from phytolith-rich pastures near Bangor, has told me that in his opinion a considerable amount of the Australian material is comparable in form with these North Wales phytoliths.[2] Descriptions and illustrations of the latter have already been published (Smithson, 1958), and the present paper deals with occurrences of sponge spicules noted incidentally during micropedological work at Bangor, both in local soils and in samples from other localities.

The Bangor District

In most North Wales soils the sponge spicules are scarce, fragmental, and presumably transported (Figs. 1–7), the opal content of the soil

[1] The present paper does not cover cases of fossil *chert* sponge spicules contributed to soils by the parent rock (Smithson, 1956).

[2] Since the above was written, Professor Leeper has kindly sent me a separation from an extremely opal-rich soil at Mt. Gellibrand, Victoria, and we are now agreed that the opal in it is almost entirely of plant origin.



FIGS. 1–30. Sponge spicules and phytoliths.

Figs. 1–7. Sponge spicules from a podzol (B horizon), Bodafon Mountain, Anglesey, Grid Ref. SH/470852. Figs. 4 and 5 show the same tetraxonid spicule in two positions of focus.

Fig. 8. Sponge spicule from a marshy mountain soil, near Lake Ogwen, Caernarvonshire, Grid Ref. SH/677603.

Figs. 9–11. Sponge spicules from soil at a depth of 12 in. in drained marshland, Malldraeth, Anglesey, Grid Ref. SH/455734.

Figs. 12–17. Phytoliths from the above sample.

Figs. 18–22. Sponge spicules from a podzol, the New Forest, Hampshire, Grid Ref. SZ/280070. Figs. 21 and 22 show the same tetraxonid spicule in two positions of focus.

Figs. 23–25. Sponge spicules from a xerorendzina, Ecija, Seville, Spain.

Figs. 26–30. Sponge spicules from 'muck' soil, Volusia County, Florida, U.S.A.

being dominated by phytoliths. When the mineral fractions are mounted in Canada balsam the opal particles are very noticeable by reason of their very low refractive index and consequent bold outline. Yet since many of the phytoliths are rod-like, a search for sponge spicules requires careful attention to details of form. In some samples, however, such as the B horizon of the Bodafon Mountain podzol, Anglesey, sponge spicule fragments have been readily detected not because they are unusually abundant but because in this profile the phytoliths are concentrated in the A horizon. For most of these widely disseminated spicules it is not possible to determine whether they are marine or freshwater. The spicule shown in Figs. 4 and 5 is an exception since it exhibits the four-branched form which Dr. Clifford Jones tells me is secreted only by certain marine sponges which are rare on our shores. Nearby there are many square miles of marine spicule-bearing silt exposed at low tide, but whether there has been appreciable transport, e.g. by wind-borne spray or by the feet of birds, is a matter for surmise.

In some very wet places an abundance of undamaged spicules suggests formation on or near the site (Figs. 8–11). One of the most interesting sites studied was a pasture on Malldraeth, Anglesey. Before considering the siliceous organic content of the soil at this place it is important to know something of the recent history of the area (Greenly, 1919). Malldraeth appears to have been a narrow arm of the sea, some 9 miles long, which has gradually become filled with alluvium. Attempts at reclamation date back at least to the sixteenth century, but until 1788 the whole valley was liable to flooding by sea water at spring tides. In that year work was commenced on a sea-dam across the depression 3 miles from the mouth of the inlet, and the subsequent drainage works were virtually completed by about 1821. The site studied, although more than 4 miles from the sea-dam, is only about 10 ft. above mean sea level, and at a depth of about 12 in. the soil is particularly rich in sponge spicules (Figs. 9–12) and diatoms, most of them unbroken. Examining the diatoms, Mr. N. Woodhead recognized 18 freshwater, 2 brackish, and 2 saline species. Dr. Clifford Jones, after an independent examination of the material, stated that he 'had little doubt that spicules of the freshwater sponge *Spongilla lacustris* were present' adding that 'one spicule might possibly belong to a marine sponge such as *Halichondria panicea*'.

The phytolith assemblage of this soil sample consists largely of rod-like bodies (Figs. 12–17) and differs in many ways from that of the surface soil. The top 2 in. yielded a phytolith assemblage similar to that previously reported for another Anglesey pasture (Smithson, 1958), but in the present case many broken sponge spicules and diatoms were present. It may be concluded, therefore, that the formation of the 'organic silica' of the lower horizon occurred *in situ* on marshy ground liable to occasional incursions by salt water and carrying a vegetation different from the present one, i.e. conditions consistent with those which existed until about 180 years ago. At that period some of this spicule-rich material could no doubt have been carried away on the feet of birds and mammals, and transported to soils on higher ground.

Other Localities

Other British and foreign examples observed during soil studies at Bangor will be only briefly noted.

Samples collected by my colleague, Mr. R. I. Davies, in the New Forest, Hampshire, contained damaged sponge spicules, presumably transported (Figs. 18–22), but for only one was it possible to determine the habitat (Figs. 21, 22; four-branched and therefore marine). From a calcareous soil near Seville, Spain, Dr. G. Paneque has obtained an abundance of sponge spicules (Figs. 23–25), some at least being marine (e.g. Fig. 23), while Dr. P. Arevalo has obtained some highly abraded examples from the Spanish Sahara. A Florida 'muck' soil, in a collection of soils obtained from Ward's Natural Science Establishment, Rochester, New York, was rich in sponge remains (Figs. 26–30) including what Dr. Clifford Jones identifies as an amphidisc (Fig. 28) characteristic of the Ephydatia, a group of freshwater sponges which also secrete spicules of the type shown in Figs. 26 and 30. In this soil the perfection of many of the spicules is strong evidence of recent development *in situ*.

In all these examples phytoliths were also present, most of the shapes suggesting grasses as a likely source.

Separation and Recognition

Methods of treating soil to obtain concentrates of phytoliths and of verifying that they consist of opal have been described in a previous paper (Smithson, 1958), and are equally appropriate when dealing with opal sponge spicules. These, like the phytoliths, have the settling behaviour of either very fine sand or coarse silt. Most of them are long spindle-shaped objects, often slightly curved and usually having a conspicuous central canal although sometimes only a fine central line is seen. In some the canal tube is open at both ends, but some have closed ends, either slightly tapered (Figs. 2, 20) or bulbous (Figs. 6, 24). The surface is usually smooth although in some genera minute rugosities are characteristic. Many of the spicules are obviously broken, but it is difficult to determine to what extent abrasion and corrosion respectively have modified their shapes. Where sponge spicules and phytoliths occur together the former are usually quite smooth although the latter may show pitting of the surface. Exceptionally, however, one finds spicules with narrow tubular perforations, which have presumably resulted from solution, extending from the surface to the central canal (Figs. 3, 27, 29).

Conclusions

From a consideration of the above evidence the following conclusions may be drawn:

1. Spicules consisting of opaline silica and derived from extant species of freshwater and marine sponges occur widely in soils.
2. In some sites which are or have been very wet the deposition of freshwater sponge spicules has occurred *in situ*.
3. In other cases topography and natural drainage preclude such an explanation, and the broken sponge spicules found under these

conditions supports the view that they are transported. Since the possible sources of the spicules are usually at lower levels, transport by wind or by the feet of animals may account for their presence.

4. There is danger of confusion with the opal phytoliths which grasses in particular contribute abundantly to the soil. Many of these are rod-like in form and comparable in size with many sponge spicules.
5. Sponge spicules may also occur in soils as micro-fossils derived from the parent rock, but such objects are likely to consist of chert which is readily distinguishable from opal by its optical properties.

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THE USE OF CHELATING REAGENTS AND ALKALINE SOLUTIONS IN SOIL ORGANIC-MATTER EXTRACTION

L. T. EVANS[1]

(Soil Science Laboratory, University of Oxford)

Summary

The extent of organic-matter extraction tended to rise with the pH of the extractant solution, as did the proportion of the humic-acid fraction in the extracts. Chelating reagents extracted more organic matter than other extractants of comparable pH, but extraction by all reagents rose with increasing time and temperature of extraction. The equivalent weights of both the humic and fulvic fractions of alkaline extracts rose with the temperature of extraction, as did the extent of conversion of the humic-acid fraction to acid-soluble compounds. The humic-acid fraction was flocculated by various salts to a much greater extent than the fulvic fraction. The nature of soil organic-matter extraction is considered in the light of these results.

ALTHOUGH the classical method of extracting soil organic matter with caustic soda still remains quantitatively the most efficient available, there is evidence that the materials extracted may have undergone considerable modification in the process, by oxidation and hydrolysis. Hobson and Page (1932) found 0·2 N Na_2CO_3 to be rather less than half as effective as 0·5 N NaOH in extraction, but little is known of the effect of pH on the efficiency of extraction or on the degree of modification of the organic matter extracted.

Extraction of organic matter by neutral solutions is generally slight, but Simon (1929) found sodium fluoride to be an efficient extractant. Subsequently Bremner *et al.* (1946, 1949) and Hamy and Leroy (1952) have shown that neutral solutions of anions which can precipitate or form chelates or co-ordination complexes with calcium and the trivalent metal cations, which often prevent the ready deflocculation of much of the organic matter in soils, are very efficient in the extraction of humus. Bremner and Lees (1949) found that time, temperature, and repetition of extraction, and pretreatment of the soil with acid, did not greatly affect the efficiency of extractions by pyrophosphate, whereas they did influence the efficiency of extractions by NaOH. Such results may imply that, unlike NaOH, the chelating reagents extract only a specific fraction of the organic matter present in a soil, namely that flocculated by the metal cations which can be chelated by the extractant anion. If such reagents are fairly specific a procedure, more rapid and efficient than that of Tiulin (1938), for the fractionation of soil organic matter according to the dominant cation rendering it insoluble could be devised, and it is the purpose of this paper to examine this possibility further.

Experimental Methods

The soil used in all extractions was a sample of neutral topsoil from the pasture in the University Parks, Oxford, prepared to pass the 1–mm.

[1] Present address: Division of Plant Industry, C.S.I.R.O., Canberra, A.C.T.

sieve. The organic carbon content of the sample was 4·4 per cent. All extractions were carried out in duplicate in covered beakers, with occasional stirring of the 1:5 soil:extractant suspensions. After extraction, the supernatant liquid was decanted off and centrifuged, first in a bucket-type centrifuge at 3,000 r.p.m. and then in a Laboratory Sharples at 22,000 r.p.m., and the organic-carbon contents were determined by a modification of Tinsley's (1950) wet-combustion method. Periodically these determinations were supplemented by dry-combustion analyses using Rickson's (1948) method, which gave essentially the same results. After removal of the extractant salts by appropriate treatment with Amberlite resins IR–120 and IRA–400 packed in columns, the humic-acid fraction was then flocculated by making each extract 0·2 N with H_2SO_4, and centrifuged off after standing overnight. This conventional fractionation was used, along with other empirical criteria, in attempts to compare the properties of different extracts—the fundamental problem in all such work—but since no single criterion was entirely adequate the data from the fulvic-humic fractionations, salt flocculations, and determinations of colour intensity, composition, and cation exchange capacity will be quoted only when relevant.

Effect of pH and Extractant Anion

The results given in Fig. 1 indicate that, with both 0·1 N and 0·4 N alkaline solutions, organic matter extraction becomes significant only above pH 8·5, when it rises sharply, to an extent depending on the concentration of the extractant. From pH 9 to pH 10 the increase in extraction rate seems to be relatively small, but above pH 10·5 it becomes very marked, and more or less independent of the concentration of the extractant. As may be seen from Table 1, most of the organic matter extracted at the lower pH values belongs to the acid-soluble fulvic fraction. In the more efficient extractions at higher pH values a much greater proportion of the extracted organic matter falls in the humic-acid fraction, except in the caustic-soda extracts, in which some modification of the deflocculated humus may have occurred.

With the other extractants given in Table 1 similar pH effects were also obtained; with both fluoride and pyrophosphate the extraction rate was scarcely affected by increase in pH up to 8·6, but in more alkaline solutions extraction was noticeably greater. With orthophosphate solutions the extraction rates were comparable with those of the carbonate and caustic soda series at similar pH values.

But whereas neutral solutions of sulphate, chloride, orthophosphate, and acetate did not extract organic matter to any significant extent, neutral solutions of pyrophosphate and fluoride did, which confirms the results of Bremner and Lees (1949). However, extraction from the present soil by sodium fluoride—which would presumably be most effective with organic matter rendered non-dispersible by the presence of aluminium ions on its exchange complex—was much less effective than with any of the soils used by them. It may also be seen from Table 1 that the pyrophosphate extracts contained a much lower proportion of fulvic acid than other extracts, which suggests that their efficient

extraction in neutral solution owes much to the ability of pyrophosphate to disperse the more readily flocculated humic-acid fraction.

Bremner *et al.* (1946) found a striking parallelism between the amounts of heavy metal cations and of organic matter extracted by various reagents. In the present experiments, when the various centrifuged extracts

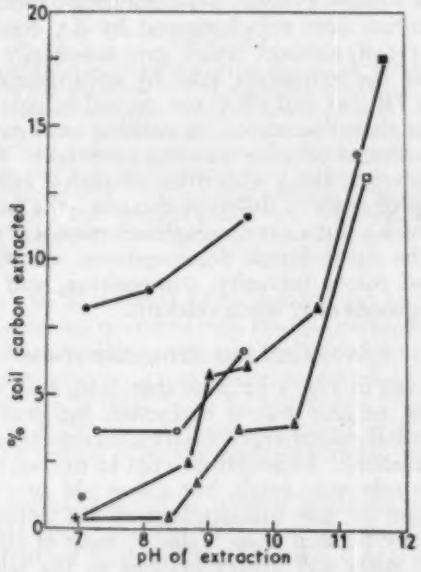

FIG. 1. The effect of pH on the extraction of soil organic matter from Oxford Parks soil by various sodium salts after two days at 17° C. ■ with 0·4 N NaOH; □ with 0·1 N NaOH; ▲ with 0·4 N carbonates; △ with 0·1 N carbonates; + with Na_2SO_4; ⊙ with 0·4 N orthophosphate; ● with 0·4 N pyrophosphate; ○ with 0·4 N sodium fluoride.

were dried and ashed, marked differences in the coloration of the residues were apparent, the most striking being the brick red colour of the pyrophosphate extract ash. Analyses made on one series of extracts, before resin treatment for removal of the extractant salts, gave Fe/Al ratios of 16·4, 5·0, and 0·68 in the pyrophosphate, carbonate, and fluoride extracts respectively; in no extract was calcium nearly as abundant as the sesquioxide metals. The presence of iron and aluminium in the extracts is no proof of their association with the extracted organic matter in the soil, but in the present experiments it was found that even after extensive dialysis, fractional precipitation and treatment with both cation and anion exchange resins the extracts still contained considerable quantities of the metal cations, in proportions similar to those in the crude extracts. This suggests an association between the trivalent cations and the

TABLE 1

The Percentage of Organic Carbon Extracted after 48 hours at 17° C. by Various 0·4 N Solutions of Sodium Salts, and the Proportion of Extracted Carbon not Flocculated by 0·2 N H_2SO_4

Extractant	*Final pH*	*% soil carbon extracted*	*% Fulvic acid*
Na_2SO_4 . . .	7·2	0·4	81·0
$NaHCO_3$ . . .	8·7	2·5	70·5
2:1, $NaHCO_3$:Na_2CO_3	9·0	5·7	54·5
1:2, $NaHCO_3$:Na_2CO_3	9·6	6·1	51·0
Na_2CO_3 . . .	10·7	8·3	49·8
NaOH . . .	11·7	17·4	56·0
Orthophosphate . .	7·1	1·2	..
	11·3	13·8	..
Pyrophosphate . .	7·1	8·1	34·4
	8·1	8·8	..
	9·6	11·7	41·3
Fluoride . . .	7·3	3·7	..
	8·6	3·8	..
	9·5	6·8	52·0
Oxalate . . .	9·8	10·1	..
Citrate . . .	8·7	10·6	..

extracted humus, and a specific action by pyrophosphate and fluoride in extraction.

Time of Extraction

With the Oxford Parks soil there is always a very striking difference between neutral pyrophosphate and alkaline extracts evident about half an hour after mixing: whereas the latter are straw coloured, the pyrophosphate extracts are quite black.

However, the results given in Fig. 2 indicate that although the pyrophosphate is initially rather more rapid in extraction than either carbonate or caustic soda, with rather less subsequent extraction the differences are not as great as might be expected from the differences in coloration, which presumably reflect the higher proportion of the much darker humic-acid fraction in the pyrophosphate extracts.

Temperature of Extraction

From Table 2 it may be seen that although increase in temperature increases the extent of extraction by NaOH much more than of that by pyrophosphate, as found by Bremner and Lees, the effect of temperature on extraction by pyrophosphate and fluoride is of the same order as that on bicarbonate-carbonate extractions.

The effect of temperature of extraction on some properties of several alkaline extracts may be seen in Table 3.

In the mildly alkaline extracts (pH 9·1) the increased efficiency of extraction at higher temperatures is accompanied by an increase in the proportion of the humic-acid fraction. It is also accompanied by changes

in the properties of the two conventional fractions, as may be seen from the intensity of their coloration and from the mean values for their equivalent weights as determined from potentiometric titration curves

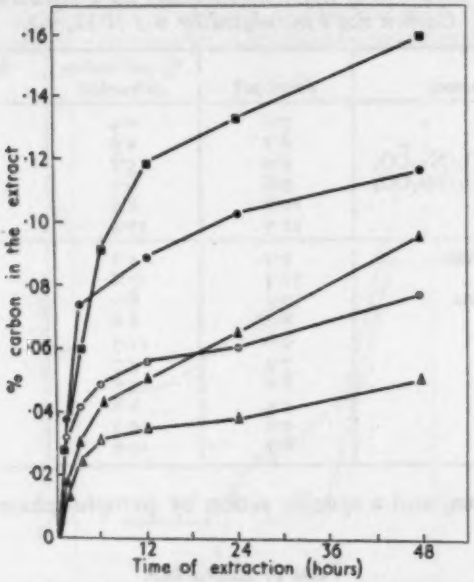

FIG. 2. The effect of time on the efficiency of extraction of organic matter from Oxford Parks soil by various 0·4 N reagents. ■ with NaOH at 17° C. (pH 11·7); △ with $NaHCO_3/Na_2CO_3$ at 17° C. (pH 9·1); ▲ with $NaHCO_3/Na_2CO_3$ at 35° C. (pH 9·1); ○ with Na pyrophosphate at 17° C. (pH 7·0); ● with Na pyrophosphate at 35° C. (pH 7·0).

TABLE 2

The Effect of Temperature on the Percentage Extraction of Carbon by Various 0·4 N Reagents, after 2 Days

Extractant	*pH*	*% soil carbon extracted*		
		at 17° C.	*at 35° C.*	*at 57° C.*
2:1 $NaHCO_3$:Na_2CO_3 .	9·1	5·7	10·8	21·4
1:2 $NaHCO_3$:Na_2CO_3 .	9·6	6·1	..	24·0
NaOH	11·7	17·4	36·9	59·5
$Na_4P_2O_7$ . . .	7·1	8·1	13·0	19·8
$Na_4P_2O_7$ . . .	9·3	11·7	15·6	24·6
Na F	9·4	6·8	..	25·6

with barium hydroxide. Such changes could be due to changes in the organic components extracted or to modification of the extracted organic matter. In an attempt to examine the latter possibility some washed, twice precipitated, humic-acid floc from an extraction at pH 9 was deflocculated in various extractant conditions for two days and then

TABLE 3

Some Properties of Several Alkaline Extracts

Extractant	Temperature °C.	pH	% soil carbon extracted	Fulvic acid fraction			Humic acid fraction		% conversion of Humic Acid
				% of carbon extracted	Colour* intensity	Equivalent weight	Colour* intensity	Equivalent weight	
$NaHCO_3$ . .	17	8·7	2·5	70·5	..	..	..	..	1·5
$NaHCO_3/Na_2CO_3$.	17	9·0	5·7	54·5	31·6	392	106	315	3·6
$NaHCO_3/Na_2CO_3$.	35	9·1	10·8	48·0	36·0	480	110	339	3·8
$NaHCO_3/Na_2CO_3$.	57	9·1	21·4	40·0	24·0	517	75	362	..
NaOH . .	17	11·7	17·4	56·0	18·4	..	88	..	12·8
NaOH . .	57	11·8	59·5	53·0	11·7	..	65	..	25·8

*Determined on purified extracts, neutralized by limewater, containing 0·025 per cent C., using an EEL absorptiometer and the blue 601 filter.

reflocculated with 0·2 N H_2SO_4, and the amount of previously acid-insoluble carbon that remained in acid solution was then determined. The results are given in the right-hand column of Table 3 and indicate that although there is only a slight conversion of humic acid to acid-soluble compounds at pH 9·1, even at 35° C., the conversion at pH 11·7 is considerable, especially at 57° C. In view of these results one would expect to find a relatively high proportion of fulvic acid in caustic-soda extracts, despite the evidence from the less alkaline extracts that relatively more humic acid components are dispersed by the more efficient extractants.

Flocculation of the Extracts

Zadmard (1939) studied the effects of various chloride salts on the flocculation of a humus suspension by following the reductions in its coloration. But as flocculation proceeds the colour/carbon ratio of the supernatant liquid changes greatly—being progressively reduced—and the flocculations described here were followed gravimetrically. Fig. 3 indicates the order of effectiveness of some of the chlorides used in flocculating a mildly alkaline bicarbonate-carbonate extract, and it may be seen that with all salts flocculations approach a definite maximum, which suggests that the humic-fulvic acid fractionation is not the only one that could significantly be made. With pyrophosphate extracts all salts flocculated a much larger fraction of the organic matter than with the bicarbonate-carbonate extracts, as might be expected from their higher proportion of humic acids. Table 4 indicates that the fulvic-acid fraction is far less sensitive than the humic-acid to flocculation by electrolytes.

The results with aluminium chloride were similar to those with ferric chloride, and it is evident that even low concentrations of the trivalent cations in a soil solution would be capable of flocculating most of the organic matter, with the exception of about one-fifth of the fulvic-acid fraction of this extract.

The undried flocs from a series of flocculations with HCl, $CaCl_2$, and $FeCl_3$ were mixed with bicarbonate-carbonate, fluoride, and neutral pyrophosphate extractant solutions in the hope that differences in the extent of their deflocculation would be apparent, but in all cases

deflocculation was virtually complete. Even the $FeCl_3$-flocculated organic matter could be readily dispersed in 0·4 N $NaHCO_3$.

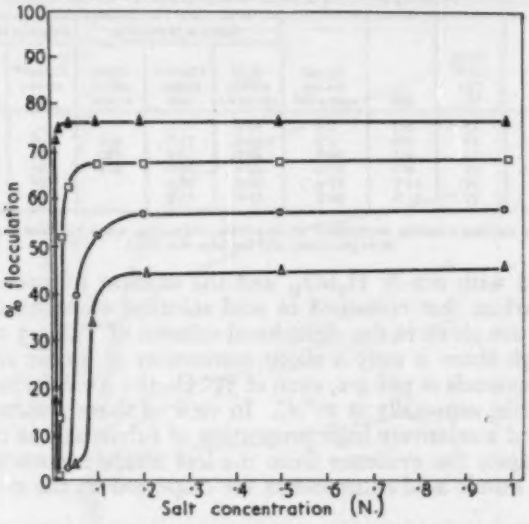

FIG. 3. Percentage flocculation of an acid organic matter extract containing 0·2 per cent. organic carbon by various salts. ▲ with $FeCl_3$; □ with $CaCl_2$; △ with KCl; ○ with HCl

TABLE 4

Percentage Flocculation of the Fulvic- and Humic-Acid Fractions of a Carbonate Extract by Increasing Concentrations of Various Chloride Salts (Initial Carbon Content of 0·053 per cent.)

Salt	Normality							
	0·005	0·01	0·02	0·04	0·1	0·2	0·5	1·0
Fulvic acid								
KCl	2·1	3·0	3·1	5·4	6·0	10·0	16·3	22·1
$CaCl_2$	2·6	3·6	4·5	7·2	9·8	16·6	24·2	31·8
$FeCl_3$	72·2	77·7	77·0	77·5	76·8	77·5	78·2	77·6
Humic acid								
KCl	2·2	2·9	3·9	5·6	65·6	72·0	81·1	91·2
$CaCl_2$	14·5	49·8	77·8	82·7	82·8	89·4	89·9	94·2
$FeCl_3$	98·0	98·6	99·8	99·5	..	98·3	..	98·6

Discussion

The results given above have indicated a general tendency for extraction of soil organic matter by all the reagents used to increase with pH, and at all pH values with increasing time and rising temperatures, there being no absolute differences between the chelating and alkaline extractants in these respects. Some of the results of Martin (1952) with sodium

fluoride, and of Hamy and Leroy (1952*a*) with oxalate, malate, and malonate suggest the same conclusion. The rapid and complete deflocculation of all undried flocs by both alkaline and chelating solutions also suggests that no extractant is likely to be sufficiently specific in action for fractional extractions to be reproducible. Even with dried preparations of $CaCl_2$- and $Fe(OH)_3$-flocs of Tiulin's fractions, Vladychensky (1947) was unable to separate them into distinct groups by fractional peptization.

On the other hand the results given above do indicate a marked efficiency in extraction by neutral solutions of pyrophosphate and fluoride, while the few ash analyses quoted support the suggestion of Bremner *et al.* (1946) that this efficiency may be due to their ability to chelate or form co-ordination complexes with calcium and the trivalent metal ions. The much greater efficiency of pyrophosphate compared with fluoride in extractions from the Parks soil may be due to iron, rather than calcium or aluminium, being the main cation preventing the ready deflocculation of organic matter in this soil, despite its neutral pH. The pronounced initial coloration of the pyrophosphate extracts, and their high proportion of the humic acid fraction—shown to be much more readily flocculated by metal salts than the fulvic acid—also suggest that the chelating abilities of the pyrophosphate anion have been involved in extraction.

In the alkaline extractions the efficiency of deflocculation does not increase regularly with rise in pH, and there is evidence of two quite separate effects being involved. In mildly alkaline conditions the extent of extraction depends on the concentration of the extractant as well as the pH, and is affected by a rise in temperature in much the same way as are neutral pyrophosphate extractions. In these conditions there was no evidence of any extensive conversion of humic-acid components to acid-soluble forms, and any increase in the efficiency of extraction results in a higher proportion of the more readily flocculated humic-acid fraction appearing in the extract, and is presumably due to effects on the extent of deflocculation of the large organic anions.

In strongly alkaline conditions additional processes, possibly oxidative and hydrolytic, are involved. The concentration of the extractant is of less importance, while the effect of increasing temperature is more marked than at lower pH values. Conversion of extracted humic-acid components to acid-soluble forms is extensive, with the result that increasing efficiency of extraction does not result in a higher proportion of the humic-acid fraction in the extracts. At what pH such modification of the extracted organic matter becomes significant cannot be stated, but it is of interest in relation to the results given here that Bremner (1950) found oxygen absorption by organic matter to become pronounced only in extractant solutions more alkaline than 0·5 M sodium carbonate at pH 10·6.

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THE ADSORPTION OF HUMIC AND FULVIC ACIDS BY CLAYS

L. T. EVANS AND E. W. RUSSELL[1]

(Soil Science Laboratory, University of Oxford)

Summary

The adsorption from suspension of the humic- and fulvic-acid components of a soil organic-matter extract by bentonite was extremely rapid, and was unaffected by temperature. For the humic fraction the extent of adsorption was: Ca and Mg systems > acid systems > K and Na systems; for the fulvic fraction: acid > Ca > Mg > K and Na systems. Only in the K systems was there an approach to the saturation of adsorption, although cation-exchange-capacity reductions ceased at a low level of adsorption. In the absence of exchangeable calcium there was a sharp fall in the extent of adsorption with rise in pH, particularly above pH 3·5.

Only a small proportion of the organic carbon in both the fulvic and humic fractions was usually adsorbed by the bentonite. The remainder of both fractions was found to be relatively unadsorbable, while the re-extracted adsorbed proportion remained highly adsorbable.

Adsorption by kaolin in K systems was as extensive as that by bentonite, but in the acid and Ca systems it was much less. For adsorption of humic carbon the order of effectiveness was Ca > acid > K, and for fulvic carbon, acid > Ca > K, as in the bentonite systems. Lepidocrocite, goethite, β-$Fe_2O_3.H_2O$, and gibbsite also removed much fulvic and humic carbon from suspension, particularly at lower pH values.

Mechanisms for the adsorption of organic colloids by clays are considered in the light of these results.

THE interaction of organic colloids with the clay fraction probably takes place in many soils, and may affect the structural condition, the extractability of the humus, and the rate of decomposition of the organic matter in soils. While the nature of the bonding forces involved in the interactions of many organic compounds with clays has been widely studied (Grim, 1953), the nature of those involved in the interaction of soil organic matter with clays is still obscure. The object of the work reported here was to study the mechanism of this association, and to examine the possibility that some fractions of soil organic matter are more readily sorbed by clays than others.

Experimental Methods

The humic colloids used were extracted from the neutral topsoil of the pastures in the Oxford University Parks with a 0·4 N 2: 1 $NaHCO_3$/Na_2CO_3 solution of pH 9·1 for 2 days at 35° C. This procedure extracted about 11 per cent. of the organic carbon from the soil. The extracts were centrifuged in a bucket-type centrifuge at 3,000 r.p.m., and then slowly run through a Sharples supercentrifuge to remove the deflocculated

[1] Present addresses: Division of Plant Industry, C.S.I.R.O., Canberra, Australia; and E.A.A.F.R.O., Kikuyu, Kenya.

clay. The extractant salts were removed by adding an excess of acid-regenerated Amberlite IR-120 resin. The extracts were then separated into the nominal humic- and fulvic-acid fractions by adding 0·2 N H_2SO_4. After standing overnight the humic-acid floc was centrifuged off, washed, deflocculated in 0·1 N $NaHCO_3$, reflocculated with acid as suggested by Forsyth (1947), centrifuged, washed, deflocculated in $NaHCO_3$ again, and treated with IR-120 resin. The two deflocculated fulvic-acid fractions were then run through columns of IR-120 resin to remove any sodium ions still remaining, and then through columns of Amberlite IRA-400 resin to remove any contaminating bicarbonate and sulphate anions. Less than 3 per cent. of the extracted organic carbon was lost from bicarbonate extracts in the course of the resin treatments.

The clay suspension used was usually a Wyoming bentonite. After particles coarser than 2μ had been allowed to sediment out, the 2 per cent. clay suspension was converted to the acid form by running through columns of Amberlite IR-120 resin. Aliquots of the acid bentonite were then immediately converted to the Na, K, Mg, or Ca forms by the addition, with vigorous stirring, of solutions of K_2CO_3 or Na_2CO_3, solid $MgCO_3$, or saturated limewater, until neutrality was attained. In experiments with a series of pH values, partial neutralization of the freshly prepared acid clay and humus suspensions was effected with 0·4 N K_2CO_3.

The adsorption experiments were made by pipetting 3–5 ml. of the requisite clay suspension, containing about 40 mg. clay, into large Pyrex boiling tubes to which were also added distilled water and the organic-matter suspension, so that the total volume of suspension used remained constant. These clay–humus systems, in duplicate, were then given end-over-end shaking, usually for two days, after which their contents were transferred to centrifuge tubes and spun at 3,000 r.p.m. for 10 minutes. The carbon content and colour intensity of the supernatant liquids were then determined, allowing the carbon contents of the centrifuged clay–humus complexes to be calculated indirectly. The lower usable limit of suspension carbon concentrations was fixed by the sensitivity of the Tinsley (1950) wet-combustion analyses, and was about 0·003 per cent. C. when decinormal reagents were used. The fulvic-acid suspension from the extract usually had about 0·04 per cent. organic carbon; the humic-acid fraction could be made as concentrated as wished on deflocculation, but was never used at a concentration higher than 0·08 per cent. organic carbon. Blanks with these highest concentrations of the two fractions invariably showed that no organic matter could be centrifuged down in the absence of clay.

In the Ca systems complete removal of the clay from suspension was readily achieved, but in the acid and the K systems it was evident from colorimetric readings that some clay remained in suspension after centrifuging; subsequent weighings showed that the amount was very small. According to Demolon (1952), low concentrations of electrolytes can be added to flocculate the clay without affecting the organic matter present, but this was not found to be so for the humus fractions used.

The Effect of Shaking Time and Temperature on the Extent of Adsorption

In all the systems used adsorption of the organic matter was rapid, at least 90 per cent. occurring within the first hour of mixing the suspensions, and adsorption being virtually complete in 24 hours. The results of the very sensitive colorimetric readings for the Ca-bentonite–humic-acid systems suggest that adsorption may continue very slowly for several days. In all the other experiments reported here shaking of the suspensions was done for 48 hours.

The usual adsorption runs were shaken at the laboratory temperature of about 17° C. However, replicates of the Ca and K systems were also run at 35° C. by shaking in a water bath, and in all cases the results were identical with those at 17° C. This is in accord with the findings of Khan (1946), but not with those of Jung (1943).

Effect of Exchange Cation and Concentration of Humus

Demolon and Barbier (1929), using a Ca-brickearth–NH_4-humate system, obtained an asymptotic curve of adsorption against concentration of humus, and from the results given in Figs. 1 and 2 it may be seen that in both the K systems, in which adsorption is least, there is an approach to saturation of adsorption at about 1·5 g. humic-acid carbon and 1·25 g. fulvic carbon per 100 g. bentonite. This upper level of adsorption is very close to that found by Jung (1943) for bentonite and peat humic acids brought to pH 7·0 with KOH.

But whereas Jung found a saturation of adsorption at approximately the same level in acid and Ca systems as in K systems, the results given in Figs. 1 and 2 indicate that adsorption is much greater in them than in the K systems, and that only in the acid-bentonite–humic-acid system is there any approach to saturation in the range of concentrations used. In the Ca-bentonite–humate system adsorption increased in a fairly linear manner up to the highest carbon concentration used, 0·072 per cent. of humate carbon in suspension, from which 18·4 g. organic carbon per 100 g. clay were adsorbed.

A further point of difference from Jung's results is that from his tables it appears that all the organic matter present in his systems was adsorbed, up to the level of adsorption saturation (the suspension concentrations are not given), and calculations from the results of Myers (1937) suggest that 90 per cent. of the added composted lucerne carbon was adsorbed in his acid systems, and 70 per cent. in his Ca systems. In the results given above, the highest proportion of the added humic-acid adsorbed was about 20 per cent., and of fulvic-acid carbon 23 per cent. in the acid systems and 14 per cent. in the neutralized systems. Evidence will be presented later that certain components of the organic-matter extract used here are more readily adsorbed than others.

From Figs. 1 and 2 it may also be seen that the two organic-matter fractions used behaved rather differently in the acid and Ca systems, the humic-acid fraction being the more adsorbed in the latter, and the fulvic fraction more in the acid systems.

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A further point of difference from Jung's results is that from his tables it appears that all the organic matter present in his systems was adsorbed, up to the level of adsorption saturation (the suspension concentrations are not given), and calculations from the results of Myers (1937) suggest that 90 per cent. of the added composted lucerne carbon was adsorbed in his acid systems, and 70 per cent. in his Ca systems. In the results given above, the highest proportion of the added humic-acid adsorbed was about 20 per cent., and of fulvic-acid carbon 23 per cent. in the acid systems and 14 per cent. in the neutralized systems. Evidence will be presented later that certain components of the organic-matter extract used here are more readily adsorbed than others.

From Figs. 1 and 2 it may also be seen that the two organic-matter fractions used behaved rather differently in the acid and Ca systems, the humic-acid fraction being the more adsorbed in the latter, and the fulvic fraction more in the acid systems.

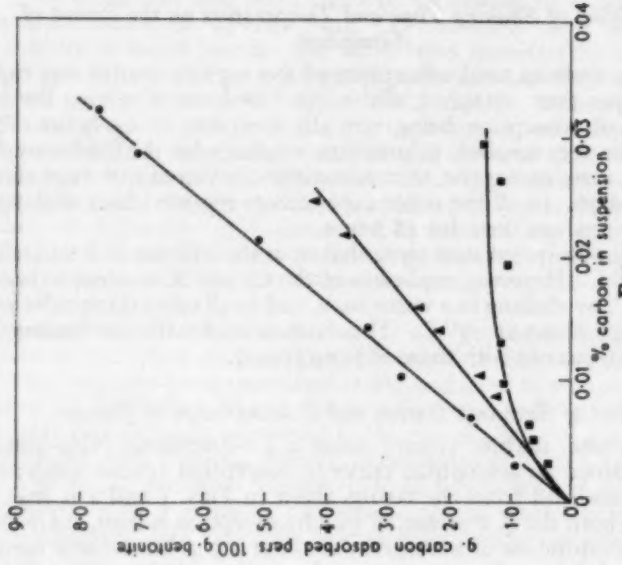

FIG. 2

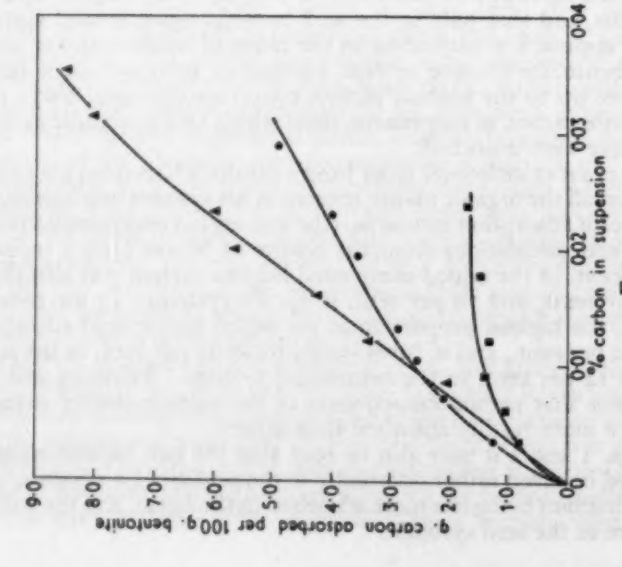

FIG. 1

FIGS. 1 and 2. Effect of the concentration of organic carbon in suspension, and of the exchangeable cation, on the adsorption of humic acid (Fig. 1) and fulvic acid (Fig. 2) by bentonite. Acid systems ●; $Ca(OH)_2$-neutralized systems ▲; K_2CO_3-neutralized systems ■.

In another series of experiments, using larger amounts of the reactants, the carbon contents of the clay–humus complexes were determined directly on the centrifuged and washed complexes rather than by reduction of the carbon in the supernatant liquid, and the results are given in Table 1.

TABLE 1

Percentage Carbon in Various Bentonite–humus Complexes Formed after Shaking 0·5 g. Bentonite with Five Successive 200-ml. Aliquots of Suspensions containing 0·0144 per cent. Carbon

System used	*Acid*	K_2CO_3 *neutralized*	Na_2CO_3 *neutralized*	Mg O *neutralized*	$Ca(OH)_2$ *neutralized*
Humic acid	2·8	1·23	1·30	3·36	3·39
Fulvic acid	4·26	1·37	1·53	1·90	3·35

If all the added carbon had been adsorbed the complexes would have contained 28·8 per cent. organic carbon. Although these results are not directly comparable with those given in Figs. 1 and 2, they do have a similar pattern. Adsorption is least in the K and Na systems, and is greatest for fulvic acid in the acid system, and for humic acid in the Ca system. The low adsorption of fulvic acid in the Mg system emphasizes the different behaviour of the two fractions. The acid and the calcium and magnesium complexes of both fractions, when dried over a water bath, produced hard, granular structures, whereas the Na and K complexes were soft and flaky.

Effect of pH on Adsorption

Suspensions of bentonite and of both organic-matter fractions (each at two concentrations) were partially neutralized with a K_2CO_3 solution, and mixed as in the preceding sections, and the results are given in Fig. 3, the reference pH values, determined potentiometrically, being those after 2 days' shaking. These did not differ greatly from those of the suspensions before mixing. In general, the humic and fulvic fractions behave similarly towards changes in pH. There is a fall in adsorption as the pH rises from 3 to 6, this fall being especially marked from pH 3·5 to 4·5. At pH 6·0 the level of adsorption of the fractions is not markedly affected by the concentration of organic matter in suspension, as was to be expected from the asymptotic nature of adsorption in the K systems, whereas in the acid systems the influence of carbon concentration is very marked. Above pH 6–7 there seems to be a small rise in the amount of adsorption.

In a series with bentonite brought to pH 9·0 from the acid condition (after resin treatment) adsorption was consistently greater than at pH 7·0. But when a series at pH 9·1 was carried out with native bentonite, which had never been converted to the acid form, no measurable adsorption occurred with either humic or fulvic acid over the entire concentration range used. This result indicates that, despite subsequent neutralization within a few hours of resin treatment, preliminary conversion of bentonite

to the acid form has created a condition in which the clay suspension remains more reactive to humus compounds. This condition is probably the presence of aluminium ions or compounds on the clay surface and one cannot conclude, as Jung has done, that adsorption of organic compounds by such clay can only be due to polar bonding forces.

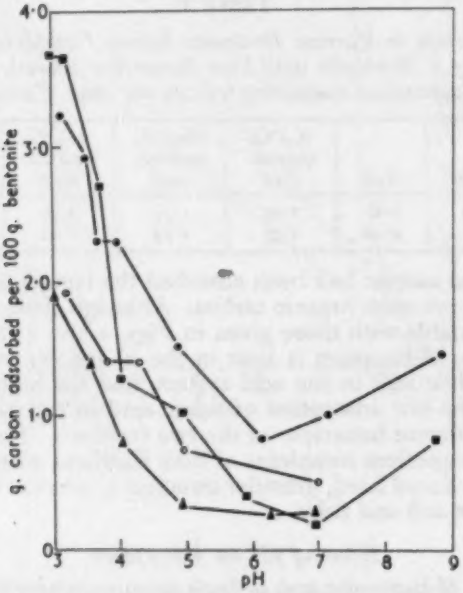

FIG. 3. Effect of pH on the adsorption of humic and fulvic acids by bentonite. Fulvic acid: at suspension concentration of 0·0194 per cent. C ■; at suspension concentration of 0·0118 per cent. C ▲. Humic acid: at suspension concentration of 0·0255 per cent. C ●; at suspension concentration of 0·012 per cent. C ○.

Attempts were made to block aluminium activity by pretreatment of the clay with morin (3:5:7:2′:4′ pentahydroxy flavone), but the results were inconclusive.

The Preferential Adsorption of Certain Components of Soil Organic Matter by Clays

Many organic compounds, such as gelatin and casein, nucleic acids, starch, pectin, and tannic acid, were adsorbed to varying extents by all the clay systems used. But the fact that less than one-fifth of the humic- or fulvic-acid carbon present in suspension was adsorbed suggested that organic compounds which are not readily adsorbed are present in both fractions of the humus extract used. It is also possible that the most readily adsorbable components of the soil organic matter were not extracted by the relatively gentle procedure used.

When a Ca clay was shaken with a fulvic-acid extract the supernatant liquid was always lighter in colour per unit of carbon than one would expect, and when shaken with a humic-acid extract it was always darker. Thus in one experiment with a fulvic-acid suspension the clay removed 16 per cent. of the added carbon, but reduced the colour by 36 per cent., while with a humic-acid suspension it removed 19 per cent. of the carbon but only reduced the colour by 15 per cent. This work was only done with Ca systems because in other systems some clay always remained deflocculated in the supernatant suspensions. But the results suggest that some of the darker components of the fulvic-acid fraction and the lighter coloured ones of the humic-acid fraction are preferentially adsorbed.

That bentonite does in fact adsorb the different compounds present in the fulvic and humic fractions to different extents was proved by removing the supernatant liquid from one adsorption experiment and adding another aliquot of bentonite to it, and taking the second supernatant and again adding clay to it. This experiment was carried out with Ca systems, using both organic-matter fractions. Over the range of humus concentrations used adsorption of both fractions was linearly related to their concentration. In the fulvic-acid systems adsorption by the second lot of bentonite from the supernatant liquid from the first adsorption was far less than that at equivalent carbon concentrations in the first run, while there was virtually no adsorption of organic carbon in the third run, as may be seen from Table 2 where each entry is the mean value for each series of adsorptions.

TABLE 2

The Effect of Repeated Additions of Clay to a Fulvic and a Humic Suspension using a Ca-*bentonite System*

	% added carbon adsorbed		
	First series	*Second series*	*Third series*
Fulvic suspension	15·8	2·7	0
Humic suspension	12·8	10·6	7·3

With the humic acid the reduction in the extent of adsorption, because of previous adsorption from the fraction, was not nearly so pronounced, but was still apparent.

A third method was also used to demonstrate the different adsorbabilities of the various constituents of the organic-matter extract. 15 g. acid bentonite were shaken up with a litre of the unfractionated organic extract, the clay–humus complex was centrifuged off, washed with water several times, and then re-extracted with 2:1 $NaHCO_3/Na_2CO_3$. This dispersed nearly all the adsorbed organic matter, and, after centrifuging, the humus suspension was then run through the exchange columns. The originally unadsorbed fraction and the extracted adsorbed fraction were then subjected to the usual adsorption series in both acid and Ca systems, with the results given in Fig. 4. In both systems about 50 per

cent. of the previously adsorbed organic matter has been readsorbed, a far higher proportion than in either the previously unadsorbed fraction or the humic and fulvic fractions used before. This confirms the conclusion that certain components of the extract used are more readily adsorbed by bentonite than others. The fact that the difference in

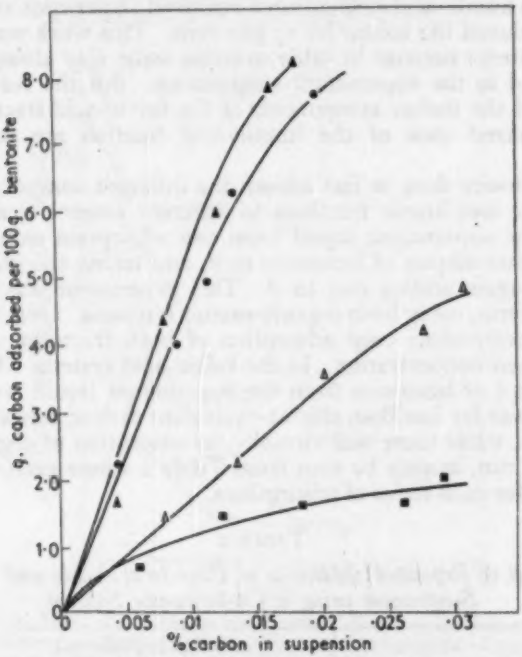

FIG. 4. The adsorption of the previously adsorbed and unadsorbed fractions of a soil organic-matter extract by acid and $Ca(OH)_2$-neutralized bentonite. Previously adsorbed fraction: acid system ●; Ca system ▲. Previously unadsorbed fraction: acid system ■; Ca system △.

adsorbability between the two fractions is less marked in the Ca systems than in the acid systems in which the original adsorption was made suggests that different organic components may be involved in adsorption from the two systems.

Cation-Exchange-Capacity Reductions

Conductometric measurements were made on replicates of the acid bentonite–humus suspensions used in the adsorption experiments, so that the changes in cation-exchange capacity of such systems could be related to the curves for the adsorption of organic matter. Of the various bases tried, a dilute solution of $Ba(OH)_2$ was found to give the most reproducible final inflexions in its conductometric titration curves with both bentonite and the organic-matter fractions. Two series of titrations

were made with each fraction and in all cases the results were similar to the set showed in Fig. 5. It has already been seen that adsorption of fulvic components from acid suspensions increases in a linear manner with the carbon concentration over the range used here and one might therefore expect a progressive divergence of the exchange capacity of

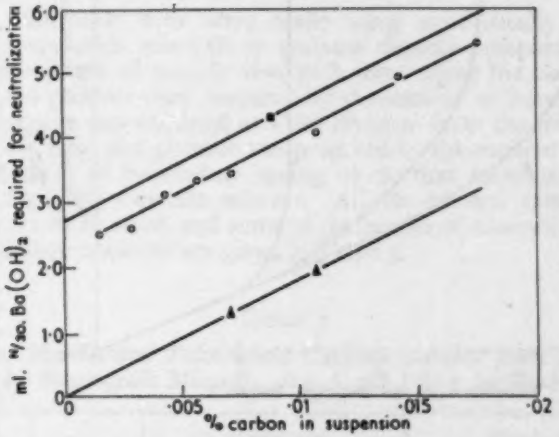

FIG. 5. Conductometric titration results for bentonite-fulvic acid systems. Fulvic acid suspensions alone ▲; expected values for fulvic acid+bentonite if no reduction in cation exchange capacity took place on mixing ■; actual values for bentonite-fulvic acid suspensions ○.

the system from the total for the separate components, whereas in actual fact such divergence ceases at a very low carbon level corresponding to a loss of exchange capacity by 1·63 g. fulvic acid and 1·05 g. humic acid carbon per 100 g. bentonite. Some calculations from the results given by Myers (1937) show that adsorptions in his systems also continued far beyond the minimum in his exchange-capacity curves, an important possibility apparently overlooked by Jung (1943). Reductions in cation-exchange capacity were also obtained with many organic compounds, including starch, so that the conclusion cannot be drawn that such reductions are due entirely to ionic reactions of the organic matter with the clay; steric hindrance effects may also be involved.

Adsorption of Organic Matter by Kaolin

A few adsorption experiments like those with bentonite were carried out with unfractionated St. Austell kaolin, and the results are given in Figs. 6 and 7. In all systems there was an approach to saturation of adsorption in the concentration range used, this occurring at about the same level as for bentonite in the K systems.

In the acid and Ca systems adsorption was greater than in the K systems, but much less than in the equivalent bentonite systems.

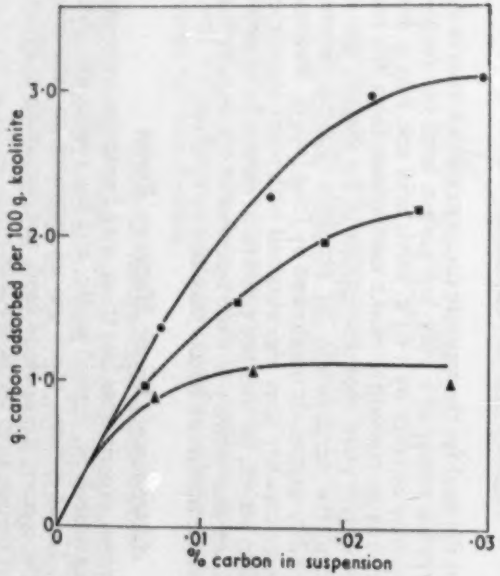

FIG. 6

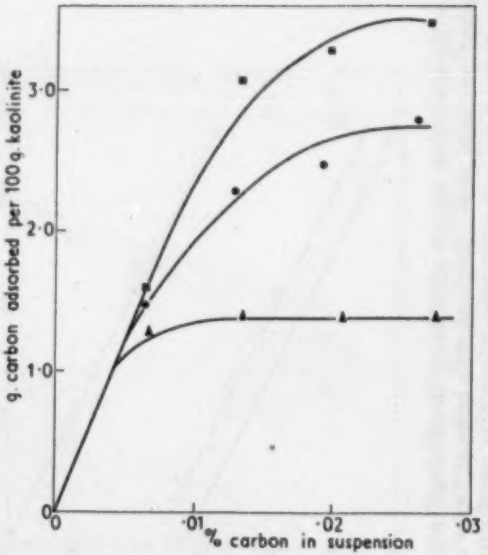

FIG. 7

FIGS. 6 and 7. Effect of the concentration of organic carbon in suspension, and of the exchangeable cation, on the adsorption of fulvic acid (Fig. 6) and humic acid (Fig. 7) by kaolinite. Acid systems ●; $Ca(OH)_2$-neutralized systems ■; K_2CO_3-neutralized systems ▲.

However, the same pattern is observed in that fulvic acid is adsorbed to a greater extent than humic acid in the acid systems, whereas the humic fraction is the more adsorbed in the Ca systems.

Adsorption of Organic Matter by Sesquioxides

A few adsorption runs were made using synthetically prepared hydrated sesquioxide minerals in systems directly comparable, apart from considerations of particle size, with those using the clays. Lepidocrocite and goethite were prepared by the method of Schuylenburgh (1949), boehmite was obtained as Cera Hydrate from the British Aluminium Company, and gibbsite was prepared by the method of Weiser (1935). Because of insufficient ageing of the last mentioned it was probably a gibbsite-bayerite mixture. All the mineral samples used passed the 60-mesh sieve, and some of the results of adsorption experiments with these minerals are given in Table 3.

TABLE 3

Amounts of Humic- and Fulvic-Acid Carbon Adsorbed from Suspension by Sesquioxide Minerals, as g. C per 100 g. Mineral

		Fulvic acid		*Humic acid*	
	pH	*0·0159%* C	*0·0318%* C	*0·0159%* C	*0·0318%* C
Goethite	3·2	4·26	4·51	4·36	4·59
Lepidocrocite	3·2	4·43	4·89	4·56	4·92
,,	5·0	3·23	..	3·31	..
,,	7·0	2·97	..	3·08	..
$\beta Fe_2O_3.H_2O$	3·2	2·53	3·15	2·61	3·23
Gibbsite	3·2	1·41	1·63	1·90	2·12
,,	5·0	3·42	..	3·48	..
,,	7·0	2·28	..	2·31	..
Boehmite	3·2	0	0	0	0

Although more of both fractions is adsorbed from the more concentrated organic-matter suspensions, the increases in adsorption are by no means proportional to the increases in concentration. Despite the much smaller size of the bentonite particles both lepidocrocite and goethite have removed more of both organic-matter fractions from solutions at the lower concentration than did the clays, on a weight-for-weight basis. The two natural polymorphic varieties of hydrated iron oxide are certainly the most active of the sesquioxides used here in humus adsorption, but such systems are hardly comparable with natural soil conditions. The reduction of adsorption of the two fractions by lepidocrocite with rising pH were not as marked as expected, while with the gibbsite-bayerite adsorption was actually greater at the higher pH values, results which suggest that free ionic iron and aluminium are not alone involved in the removal of organic matter from suspension.

Discussion

In the K_2CO_3-neutralized systems, up to 1·5 and 1·25 g. humic- and fulvic-acid carbon respectively were adsorbed per 100 g. bentonite, figures which compare closely with Jung's (1943) estimate of 2·2 g. peat humus (i.e. about 1·25 g. carbon) adsorbed per 100 g. KOH-neutralized bentonite at saturation. Jung suggested that Van der Waals' forces were responsible for adsorption in such systems, since indirect evidence from viscosity measurements indicated that adsorption could be reduced by a rise in temperature. Hendricks (1941) and Grim, Allaway, and Cuthbert (1947) have presented evidence that some large organic molecules may be held on clay surfaces by Van der Waals' forces, and Jung calculated that the level of adsorption mentioned above corresponded with that of a complete monolayer of humus molecules on the clay surface. However, no effect of temperature on the extent of adsorption in K systems was found in the present study, nor was any found by Khan (1946).

Hydrogen bonding of the type discussed by Bradley (1945) might also be involved in clay–humus associations, and if the humus molecules are strongly polarized it is also possible that they could be oriented around the exchangeable-potassium ions of the clay (cf. Russell, 1934). However, the fact that the native sodium bentonite, which had not been preliminarily converted to the acid condition by electrodialysis (as used by Jung) or by exchange resin treatment (as used in the present study) and then neutralized, showed no measurable adsorption of either organic-matter fraction over a wide range of concentrations suggests that Van der Waals' and hydrogen-bonding forces are unlikely to be of great importance in the adsorption of humus particles by K- or Na-bentonite. Bentonite converted first to the acid condition and then brought to its original pH (9·1) with Na_2CO_3 showed marked adsorption of both fractions. Thus the preliminary conversion of the bentonite to the acid form has created a condition in which the clay remains permanently more reactive towards humus. This condition is probably the release of lattice aluminium. The fact that in K_2CO_3-neutralized systems kaolinite removed almost as much humic and fulvic acid from suspension as did bentonite is more in accord with the suggestion that some form of aluminium activity is involved than with the suggested operation of polar bonding forces, since the low-charge density of the kaolinite could hardly induce as much polar sorption as the high-charge density of bentonite.

In the Ca-neutralized systems adsorption of both humus fractions was much greater than in the corresponding K-neutralized systems, and showed no sign of approaching saturation, even when up to 18·4 g. humic carbon per 100 g. bentonite had been adsorbed. Such results are more in accord with those of Demolon and Barbier (1929) than with those of Jung (1943). The adsorptive forces which are operative in the K systems may also be active in the Ca systems, but other bonding mechanisms must also be involved. Washed bentonite–humus complexes from all systems were examined at the Macaulay Institute, Aberdeen, for their *c*-axis spacings and in no case was there any evidence

of penetration of humus between the bentonite laminae, although Greenland (1956) found that a soil polysaccharide from the fulvic-acid fraction was absorbed on the interlamellar surfaces of bentonite. Sedletsky and Tatarinova (1941) and Jung found no evidence of lattice penetration by humus molecules, and reactions at the interlamellar exchange sites cannot be invoked to explain the very large adsorption in the Ca systems used in the present study. The exchangeable calcium ions at the lattice edges may act as bridge linkages between the clay and humus particles, as suggested by Meyer (1935), and such adsorptions of humus at the crystal edges have been noted by Flaig and Beutelspacher (1951) in their electron-microscope studies with kaolinite. The finding of Lynch *et al.* (1957), that an increase in the extent of methoxylation of pectin greatly reduced the extent of its adsorption by Ca-montmorillonite, supports Meyer's concept of clay–humus interaction. Additional adsorption of humus from suspension may be due to the calcium ions linking humus particles adsorbed at the lattice edges to further humus particles from suspension, the relatively large clay particles acting as centres for what may be akin to flocculation of the otherwise stable humus suspension. In this connexion it may be noted that the more readily flocculated humic-acid fraction is adsorbed to a greater extent in the Ca-neutralized systems than the less readily flocculated fulvic-acid fraction.

In the acid systems adsorption was also much greater than in the K systems, especially with the fulvic-acid fraction, and again showed no evidence of impending saturation at the organic-matter concentrations used. These results are also very different from those of Jung. Myers (1937) found that acid Putnam clay removed more composted lucerne from suspension than Ca-Putnam did. He concluded that polar bonding forces must therefore be involved, but the presence of exchangeable aluminium ions and the ability of the amino groups of complex organic molecules to displace exchangeable cations from clay surfaces are more probably responsible for humus adsorption in acid systems. The experiments carried out at series of pH values showed that, for both fractions, adsorption decreased rapidly as the pH rose from 3·5 to above 4·0, and then continued to diminish slowly as the pH rose to neutrality. Aluminium ions, which would be present below pH 4·0, can flocculate both the humus fractions at very low concentrations. Above pH 4 hydrogen ions probably dissociate from some of the water molecules surrounding the aluminium ions, so that charged units of the type suggested by Schofield (1946) are formed until, above pH 5, these units are precipitated as $Al(OH)_3$, perhaps on the clay surfaces. The experiments with gibbsite and lepidocrocite showed that even at neutral pH values, the hydrated aluminium and iron oxides could still remove noticeable amounts of both humus fractions from suspension.

However, although the humic-acid fraction is more susceptible to flocculation by aluminium ions than is the fulvic fraction, both bentonite and kaolinite in acid systems adsorb more fulvic acid than humic acid from suspension. Ensminger and Gieseking (1939) showed that proteins could be adsorbed by montmorillonite, their free amino groups displacing exchangeable cations, and the exchanged molecules causing marked

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increases in the (001) spacing of the clay. Adsorption of proteins increased as the pH fell, and was prevented by deamination. Goring and Bartholomew (1952) obtained similar results with nucleic-acid uptake by bentonite, and Swaby (1950) found that deamination of humates reduced their aggregating effect on soil. But there was no evidence of increased (001) spacings in the acid clay–humus complexes produced, and no marked amino-group inflexions in the potentiometric-titration or spectrograph-adsorption curves of the humus preparations used in the present study.

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MOLYBDENUM IN THE LOWER LIAS OF ENGLAND AND WALES IN RELATION TO THE INCIDENCE OF TEART

H. H. LE RICHE

(Soil Survey of England and Wales,
Rothamsted Experimental Station, Harpenden)

Summary

An explanation is offered for the fact that the toxic levels of molybdenum occurring in the Lower Lias soils of Somerset have not been found in soils of Glamorgan, apparently derived from the same zones of the Lower Lias. This is attributable to the parent rock being free of the abnormally high levels of molybdenum found in Somerset, which in turn probably results from the Glamorgan Lias having been laid down close to the contemporary coastline.

Soils high in molybdenum are to be expected in the Vale of Marshwood (Dorset), but owing to the topography of this district they probably occur in such small pockets as to cause no serious trouble.

THE toxic effect of excessive molybdenum in the diet of cattle was first demonstrated by Ferguson, Lewis, and Watson (1943). They showed that a disorder occurring in cattle in central Somerset and locally known as teart was directly due to an abnormally high level of molybdenum in the soil and pasture and that the trouble could be controlled by the administration of copper to the animals. Similar effects have been reported by Cunningham (1949) in New Zealand, Barshad (1951) in California, Walsh, Neenan, and O'Moore (1953) in Ireland, and others, but in none of these cases have the circumstances been the same as in Somerset, where up to 100 p.p.m. Mo were found to occur in the soil with a general tendency to increase downwards to the parent shale.

It had previously been shown by Clarke (1855) that the disorder was associated with soils derived from the Lower Lias and by Gimingham (1914) that it also occurred in isolated areas elsewhere, as far away as Lincolnshire, when the Lower Lias was unobscured by drift.

Although the work of Ferguson *et al.* solved the agricultural problem of preventing the disorder, it raised a question which has not so far been satisfactorily answered. In the southern part of Glamorgan (see Fig. 1) the soil over large areas is also derived from the Lower Lias, but no cases of teart have been reported. In a rapid survey of the area, Lewis (1943) was unable to find any soils containing molybdenum in amounts comparable to those in Somerset. He suggested two possible explanations for this:

(*a*) that the greater rainfall and better drainage in Glamorgan have resulted in the molybdenum being leached out; or

(*b*) that the molybdenum is concentrated in the higher, more argillaceous component of the Lower Lias, whereas the soils of Glamorgan are derived only from the lower zones, which contain more limestone.

A study of the distribution of certain trace elements in the Lower Lias of England and Wales (Le Riche, 1959) has indicated that:

(*a*) the high concentrations of molybdenum appear to be confined to the lower zones from *jamesoni* downwards, some of the highest being found in the thin shale partings between limestone bands;

(*b*) it has been found to contain these high concentrations at points as far apart as Northleach (Glos.), central Somerset, and Lyme Regis (Dorset);

(*c*) the amount of molybdenum in the shale is closely related to the amount of organic matter;

(*d*) these same lower zones do not contain abnormally high molybdenum in Glamorgan.

FIG. 1

In a number of shale samples examined from the Glamorgan coast between Dunraven and Lavernock, one from the latter place was found to contain 35 p.p.m. Mo, but no others were found containing more than 5 p.p.m. In the same zone (*angulatum*) contents greater than 150 p.p.m. were common at all three English sites.

In the accompanying table, contents are given for shales from the

angulatum zone at Lavernock and Lyme Regis, the two sets from each site representing the highest and lowest concentrations of molybdenum found.

TABLE I

Corresponding Contents for Shales from Lavernock and Lyme Regis

	Mo *p.p.m.*	Cu *p.p.m.*	*Org.* C %	$CaCO_3$ %
Lavernock	35	58	2·54	37·0
	<2	34	0·78	13·6
Lyme Regis	190	63	6·22	25·5
	70	65	5·20	17·2

These figures indicate that not only are the levels of molybdenum and organic carbon much higher at Lyme Regis, but that no abnormally high amount of copper occurs at Lavernock, which could have acted as an antidote to teart. It is therefore reasonable to suggest that the absence of teart in Glamorgan is not to be attributed to the molybdenum having been leached out, but to the fact that the parent shale never contained abnormal amounts. It is probably significant that at the time of deposition, the coastline of the Liassic sea lay close to Dunraven (Trueman, 1922) and that Lavernock was the part of Glamorgan most remote from this coastline and nearest to Somerset. From this it seems likely that relatively deep water was needed for the accumulation of the type of organic matter with which molybdenum is associated.

This study of molybdenum in the Lower Lias raises another point of interest concerning teart. Some of the highest concentrations were found in the outcrop at Lyme Regis, yet no confirmed cases of teart have been reported in this area. The principal reason is that in most of the area between Lyme Regis and central Somerset the Lias is obscured by more recent deposits. In the nearby Vale of Marshwood, however, the lower zones do outcrop and soils high in molybdenum might be expected.

In these lower zones, which consist largely of interstratified bands of limestone and shale, the molybdenum content of adjacent bands has been found to be very variable. Consequently, in order to produce an appreciable area of teart soil, the land surface would need to be at only a small angle to the bedding plane. This is not the case in the Vale of Marshwood; the outcrop occurs on hillsides, where protection is also likely to be provided by a thin layer of downwashed material. Furthermore, the steep slopes will promote good drainage which Mitchell *et al.* (1957) have shown can reduce the availability of molybdenum and other trace elements to pasture plants.

Although areas of soil high in molybdenum probably occur in this district, it is unlikely that they would be larger than patches in fields, and would not be expected to cause any serious trouble with grazing animals.

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